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Toroidal Metaphotonics and Metadevices

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Abstract: Toroidal moments in artificial media have received growing attention and considered as a promising framework for initiating novel approaches to manage intrinsic radiative losses in nanophotonic and plasmonic systems. In the past decade, there have been substantial attention on the characteristics and excitation methods of toroidal multipoles- in particular, toroidal dipole- in 3D.
bulk and planar metaplatforms. The remarkable advantages of toroidal resonances have thrust the toroidal metasurface technology from relative anonymity into the limelight, in which researchers have recently centered on developing applied optical and optoelectronic subwavelength devices based on toroidal metaphotonics and metaplasmonics. In this focused contribution, we describe the key principles of 3D and flatland toroidal metastructures, and briefly highlight the revolutionary tools that have been implemented based on this topology. Infrared (IR) photodetectors, immunobiosensors, ultraviolet (UV) beam sources, waveguides, and functional modulators are some of the fundamental and latest examples of toroidal metadevices that have been introduced and studied experimentally so far. The possibility of the realization of strong plexciton dynamics and pronounced vacuum Rabi oscillations in toroidal plasmonic metasurfaces are also presented in this Review. Ultimate efficient extreme-subwavelength scale devices, such as low-threshold lasers, and ultrafast switches, are thus in prospect.

1. Introduction

The 21st Century belongs to photonics, especially because of the revolutionary developments in optics-based reliable, cost-effective, efficient, compact, and realistic technologies all around the society. Noteworthy endeavors in many fields, from chip manufacturing and lighting, healthcare and modern pharmacology to astronomy and military, have been demonstrated and established using the power of light. Futuristic and strategic technology requirements will push the limits of light towards subwavelength photonic integration and energy efficiency, beyond that of bulk optical components, silicon photonics, and plasmonic nanocircuits.\[1-5\] This integration can be attained by considering the data processing and waveguiding characteristics at more basic level, and the only possible way of overcoming those challenges is employing the concepts of metamaterials and metadevices based on structuring artificial matter at the subwavelength scales.\[6-8\] Optical magnetism,\[9-11\] asymmetric transmission,\[12-14\] hyperbolic dispersion,\[15-18\] epsilon near-zero (ENZ),\[19-22\] topological states,\[23-27\] arbitrary control of light’s trajectories and cloaking,\[28,29\] excitation of
toroidal fields and charge-current configurations,\cite{30-33} and generation of flying doughnuts\cite{34,35} are some of the fundamental discoveries that are allowed by metamaterials.

To date, several types of resonant photonic and plasmonic metamaterials have been engineered and introduced for diverse purposes. Among them, promisingly, Fano-resonant\cite{36-39} and electromagnetically induced transparency (EIT)-resonant\cite{40-44} metastructures have received copious attention owing to providing ultrasharp spectral lineshapes and an active control on the behavior of the transmitting light (e.g. slow light, beam steering, etc.).\cite{36,45-47} Although these artificially tailored bulky metamaterials have established decisive aisles for developing high-responsive and active optics-based tools, the ever-increasing demand for building the most efficient design has drove efforts to substitute these conventionally resonant structures with novel alternatives. In relation to these exploration activities, in 2007, novel optical metamaterials based on the third family of electromagnetic multipoles, \textit{toroidal multipoles}, was introduced by Marinov et al.\cite{48} Originally explored by Zel’dovich in 1957,\cite{49} the toroidal phenomenon has been elucidated by virtue of various principles of physics.\cite{32,33,50-52} In the modern electromagnetic limit, primarily, the dynamic toroidal dipoles have been observed in 3D metamolecules across the microwave regime.\cite{30} Toroidal resonant systems are well-known for producing unconventional gyroscopic-fashoned charge-current excitations’ fingerprints with hidden far-field radiation.\cite{53} While there have been extensive studies to develop subwavelength systems capable to multipolar toroidal moments\cite{54} and high-order multi-loop supertoroidal currents,\cite{55,56} of particular interest is the \textit{dynamic toroidal dipole} that can be optically driven and recognized as a ring-shaped head-to-tail configuration of magnetic dipoles, intensely squeezed within a tiny spot.\cite{30-35,55-62} Theoretically, the dynamic toroidal dipole offers physically substantial nonzero contributions to both the fundamental properties of matter and scattered radiation.\cite{63,64}

Up to now, dynamic toroidal charge-current configurations with different qualities have been excited in both planar (2D) and 3D architectures, as well as cavity oligomers from visible to IR,
terahertz (THz), and microwave frequencies.\textsuperscript{[32,33,65-73]} Owing to the ability of tightly squeezing electromagnetic fields and supporting ultrasharp resonance lineshapes, very recently, the practical use of toroidal metastructures have obtained considerable research attention.\textsuperscript{[57,69,74]} Considering the unique advantages of these spectral features, well-engineered toroidal unit cells have emerged for designing strategic subwavelength devices, such as large modulation-depth modulators,\textsuperscript{[75-80]} augmented nonlinear harmonic signal sources,\textsuperscript{[81]} high-photon yield photodetectors,\textsuperscript{[82,83]} and extremely sensitive and precise immunobiosensors.\textsuperscript{[84-87]}

This contribution aims to highlight and focus on the most recent and important devices enabled by toroidal metasurface technology. To do so, by demonstrating the principles of the toroidal context in subwavelength schemes and underlying the physics behind the formation of such spinning features, we briefly reassess the emerging toroidal photonic and plasmonic device concepts including multifunctional modulators, high-responsive photodetectors, next-generation deep-ultraviolet (DUV) light sources, ultrasensitive biosensors, pronounced vacuum Rabi oscillations, and photonic waveguides. We also highlight current scientific and engineering challenges that limit the potential applications of toroidal meta-instruments for modern nanotechnology and nanophotonics.

2. Key Principals of Toroidal Meta-Atoms

Inducing a dynamic toroidal dipole possesses the creation of a closed-loop configuration of the magnetic fields and currents rotating on the surface of a torus (Scheme 1).\textsuperscript{[67]} This scheme demonstrates the charge and current configurations for classical electromagnetic and toroidal multipoles, where the far-field radiation of each multipole is displayed artistically. Theoretically, the electromagnetic fields of these time-dependent multipoles have been discussed under the analysis of Lorentz and Feld-Tai lemmas theorems.\textsuperscript{[55]} The direction of both current loop and poloidal currents majorly depends on where the induced magnetic moments of a unit cell point out.\textsuperscript{[70]} Principally, the observation of optically driven dynamic toroidal excitations is quite challenging, due to the dominant contributions from traditional electric and magnetic multipoles to the projected far-field radiation.
pattern. However, this has successfully been addressed by structuring artificial molecules with toroidal symmetry, or large 3D metamolecules. Next, since the theoretical aspects of the toroidal multipole excitations are described comprehensively in previous review and research articles, we majorly concentrate on the excitation mechanisms of toroidal moments in 3D and planar metastructures.

2.1. 3D Metamaterials for Toroidal Mode Excitation

The discovery of the optically driven toroidal dipoles has been originally reported in 3D architectures, where Papasimakis et al. illustrated the experimental excitation of toroidal dipole resonances in the microwave dichroism spectra of chiral toroidal solenoid arrays, and right after, Kaelberer et al. demonstrated the formation of toroidal dipole modes in a microwave-resonant metamaterial using a group of four rectangular bended metallic wire strips that were settled along conjointly orthogonal planes. In this pioneering investigation (Figure 1a), metallic wire strips oriented in such a way that the front and rear pairs of the pixels interact with in-phase or out-of-phase magnetic component of the impinging beam. Technically, in the in-phase interaction regime (Figure 1b), the optically driven magnetic dipolar modes, originated from the four wire stripes, point out the same direction, leading to the formation of a distinct magnetic resonance ($M_y$). In contrast, for the out-of-phase interaction, magnetic dipole moments, associated with the front and rear pairs of proximal resonators, indicate the opposite direction, giving rise to the head-to-tail arrangement of magnetic dipoles (Figure 1c). Indeed, formation of such a feature is a strong signature of the toroidal dipole excitation. The close-up graph of the wire structure and the metamaterial stack are demonstrated in Figures 1d and 1e, respectively. The measured spectral responses (i.e. transmission and reflection profiles) of the metamaterial are illustrated in Figures 1f and 1g, respectively. In these panels, the magnetic and toroidal resonances, resulting from the in-plane and out-of-plane interactions, are symbolized by I and II, respectively. Following, to understand the excitation principle of the toroidal dipole, the multipole decomposition profile was computed for the radiated power from different modes (Figures 1h). One can easily observe the drastic damping of the radiative electric dipole ($P_z$) mode around the toroidal...
resonance and the dominancy of the magnetic and toroidal modes along the spectra. Besides, magnetic energy density contours in Figures 1i and 1j explicitly indicate the difference between magnetic-field distributions at the corresponding magnetic and toroidal dipole resonant frequencies.

Further investigations in the development of 3D metamaterials to support pronounced toroidal resonances have led to the emergence of mid-infrared (MIR) toroidal meta-atoms.\cite{71,72} Compared with their microwave and THz counterparts, these studies accompanied with successful excitation of multiple toroidal resonances at shorter wavelengths. Foldable metallic unit cell in a 3D fashion is one of the most recent examples of toroidal metaplatforms at MIR wavelengths.\cite{71} Figure 1k shows an artistic picture of the foldable plasmonic meta-atom that sustains double toroidal dipole resonances. The scanning electron microscopy (SEM) images of the fabricated structure are presented in Figures 1l and 1m with different magnifications. Figures 1n and 1o illustrate the calculated and measured transmission spectra of the plasmonic metamaterial for $y$-polarized incidence. In both panels, two pronounced toroidal dipole-resonant dips appeared at $\omega_{T1}=73$ THz and $\omega_{T2}=83.5$ THz with quality-factor ($Q$-factor) of 24 and 26, respectively. To quantitatively study the origin of these modes, the radiation power of the induced multipoles have been calculated through volume current density of the 3D metastructure, as shown in Figure 1p. Clearly, only the electric/magnetic dipole, electric/magnetic quadrupole, and toroidal dipole modes significantly contribute to the metamaterial’s spectral response, while the influence of the other high-order multipoles is negligible. Although electric and magnetic quadrupole moments are also exist at specific frequencies, the intensity of the toroidal component ($T_z$) at $\omega_{T1}$ and $\omega_{T2}$ is much stronger than that of electric quadrupole ($Q_e$) and electric dipole ($P_y$) moments, respectively. It is important to note that $T_z$ does not contribute directly to the far-field radiation at normal incidence, however, indirectly incorporates through the excited the plasmon mode. Beyond that, the net electric dipole moment and, thus, the radiative losses are remarkably minimized, resulting in the excitation of much narrower toroidal lineshapes.

The obtained trend in spectral analyses can be further verified by calculating the magnetic field and surface current distributions at the resonance wavelengths, as illustrated in Figures 1q and 1r,
respectively. Here, at $\omega_{T1}$, a strong magnetic vortex appears between the adjacent unit cells. Certainly, this toroidal resonance originates from the near-field interactions between the proximal unit cells along $x$-direction, which results in substantial confinement of the magnetic field to form a magnetic vortex. At $\omega_{T2}$, the observed magnetic fields form magnetic vortices that are squeezed within each individual unit cell (Figure 1q). More precisely, the induced currents generate circulating surface currents along each resonator, resulting in a magnetic dipole which points in forward or backward direction perpendicular to the bulk metaplatform plane. In this regime, the left and right resonators support oppositely circulating currents, leading to a spinning magnetic moment perpendicular to the entire metamaterials’ surface. This yields a strong toroidal dipole moment along the $z$-axis. It should be underlined that suppression of the electric dipole moment gives rise to huge magnetic energy trapping in the folding metamaterial. Moreover, as presented in Figure 1q, at $\omega_D$, the toroidal component is very weak, since no magnetic vortex is formed. Figure 1r shows the surface current distributions in the folded plasmonic unit cell, revealing that the loop currents and subsequently the magnetic dipoles in the left and right parts of the unit cell are either opposite or parallel to each other. The head-to-tail arrangement of magnetic dipoles demonstrates the strong coupling between the proximal meta-atoms, owing to the spinning magnetic fields that induce the magnetic field vortices.

Thus far, several types of all-dielectric and plasmonic 3D metaplatforms have been designed and fabricated to support pronounced toroidal dipoles from IR to microwave frequencies, as collected and shown in Figure 2, particularly for permittivity sensing,[95] circular cross-polarization conversion,[96,97] and perfect absorption.[98] However, volumetric losses, limited access to the stored energy, challenging lithography procedures, complex numerical and theoretical analysis requirements, and incompatible integration with planar devices have stimulated researchers to develop toroidal metastructures based on flatland optics.

2.2. Planar Metastructures for Toroidal Mode Excitation

In the flatland optics limit, quasi-infinite metasurfaces, made of periodic arrays of scatterers or optical thin films, overcome the need for propagation effect by enforcing abrupt and controllable
changes of optical properties.\textsuperscript{[99,100]} In that respect, researchers have extensively focused on inducing toroidal dipoles in an artificial media consisting of meticulously engineered planar metallic and dielectric unit cells (Figure 3).\textsuperscript{[56,61,70-87,101,102]} Easy and cost-effective fabrication steps, simple modeling and quick numerical computations, compatibility with other planar devices in photonic/plasmonic circuits, as well as reduced radiative losses have inspired researchers to develop artificial media based on flatland optics toward this purpose. In principle, in an aligned planar unit cell composed of multiple resonators, the formation of a spinning toroidal feature stems from the discrepancy between the direction of induced magnetic dipole moments in proximal resonators, known as magnetic dipole-induced toroidal dipole moment.\textsuperscript{[59]} Instead, as an alternative route to the magnetic dipole-induced toroidal modes, one can also form the toroidal dipole moment based on electric dipole coupling.\textsuperscript{[103,104]}

While the excitation of toroidal dipole modes in metasurfaces has been studied both numerically and experimentally,\textsuperscript{[69]} the first experimental verification of the excitation of toroidal dipole modes was performed in all-dielectric 2D metamaterials consisting of three-member dimer assemblies based on high-index nonmagnetic dielectric disks.\textsuperscript{[105]} This work illustrates the generation of two different toroidal dipoles in the structured metasurface, called intra- and inter-cluster modes along the microwave frequencies. Figure 4a shows a schematic representation of the all-dielectric platform immersed into a dielectric medium. Since the geometry of metamolecule differs in $x$- and $y$-directions, the transmission characteristics mainly depends on the polarization state of the incident beam. This work mainly focused on $y$-polarized light and the overall response of the 2D metamaterial is defined through near-field couplings between the particles inside the clusters (i.e. intra-cluster coupling), rather than by the electric and magnetic dipole moments of individual disks. However, it is noteworthy that the mutual effect of the proximal clusters (i.e. inter-cluster coupling) of the array is considerably high. Theoretically, near-field coupling forms hybrid modes of the disk cluster and these collective modes are conventionally considered as a mixture of the electric dipole
moments generated by the incident radiation. The vortex of these electric dipole moments allows for the formation of a ring-like mode in a head-to-tail arrangement. Given that the formation of the toroidal dipole mode relies on the dielectric characteristics of the surrounding media, two different metasurface configurations have been considered, whose disks are buried into the host with either low (Design $^{(1)}$) or high (Design $^{(2)}$) relative permittivities. The radiated power from different multipoles is demonstrated in Figure 4b, where the dominancy of the toroidal dipole mode is recognizable.

Numerically obtained results for the transmitted wave through the metasurface for both Design $^{(1)}$ and Design $^{(2)}$ are presented in Figures 4c and 4d, respectively. Two pronounced resonances around 8.13 GHz ($f_1^{(1)}$) and 8.34 GHz ($f_2^{(1)}$) are considered as the fundamental resonances. Here, the second resonance in Design $^{(1)}$ ($f_2^{(1)}$) was obtained through eigenvalue analyses, because it has similar electromagnetic field properties to those of the first resonance at $f_1^{(1)}$. Figures 4e and 4f present the simulated polarization currents and intensity distributions of both electric and magnetic fields in the middle plane at $f_1^{(1)}$ and $f_2^{(1)}$. For $f_1^{(1)}$, the intensity distribution map of the magnetic field signifies the formation of three hotspots inside the cluster. Conversely, the map of the electric field demonstrates: 1) a bright hotspot in the center of the cluster and 2) three less bright hotspots on the outermost side of the dielectric disks. The closed-loop configuration of these optically driven moments creates a hybrid level in which the magnetic field lines penetrate to all three disks in the cluster. Strictly speaking, the displacement currents are focused within the disks enclosing the magnetic field lines. The interaction of particles inside the cluster leads to the excitation of such a hybrid states, hence this mode is marked as the intra-cluster toroidal dipole mode (TD$_{\text{intra}}^{(1)}$). Although $f_2^{(1)}$ does not possess a head-to-tail pattern within the cluster, it seems as a mode among the neighbor assemblies. One should note that this mode does not arise in the multipolar decomposition panel in Figure 4b, due to the formation of inter-cluster coupling, and can be merely identified from the electromagnetic near-field distribution. Here, two radiative bright hotspots and a single less-
bright hotspot inside the disks are appeared. Taking advantage of the provided results on the displacement currents and magnetic field distributions, it is possible to understand that for this collective state, the magnetic field lines are coupled to two disks of a cluster and one disk of an adjacent cluster, shaping a closed-loop distribution among them, which is marked as $\text{TD}_{\text{inter}}^{(1)}$. Similar studies have been carried out for the Design $^{(2)}$ in a medium with higher relative permittivity. The transmission spectra in Figure 4d points a slight shift in the position of the fundamental and main resonances ($f_{1}^{(2)} = 9.33$ GHz and $f_{2}^{(2)} = 9.50$ GHz). Interestingly, the behavior of the toroidal dipole mode is conserved and the variations in the permittivity of the medium did not affect the spectral response of the metasurface.

Besides the longer wavelengths, the excitation of toroidal resonances across the shorter wavelengths using planar metasystems has also been investigated extensively. For this purpose, for example, plasmonic metasurfaces have been utilized to induce pronounced and narrow linewidth toroidal modes at near-infrared (NIR) and optical frequencies. One of the pioneering works in this context is the plasmonic metasurfaces based on circular V-groove arrays, proposed by Li et al.$^{[107]}$ Both experimental and numerical studies have been conducted to validate the excitation of toroidal modes at the targeted optical frequency regime. It is shown that the unique geometry of the implemented nanostructure allows for the excitation of toroidal dipole mode when the incidence angle is $>20^\circ$. The schematic and side-view images of the metasurface are depicted in Figures 5a and 5b, respectively (exact geometries can be found in Ref. [107]). Figure 5c illustrates the focused-ion-beam image of the circular V-groove lattice and the inset displays the unit cell structure on $45^\circ$-downward front view. To define the resonant wavelengths and the position of the reflection dips, following relation for periodically arranged structures was utilized.$^{[108]}

\[ \lambda_{\text{min}} = \frac{2\pi}{k_0 \sin \theta \pm G_{\text{wm}}/} \left( \frac{\varepsilon_{w}^{\varepsilon_{d}}}{\varepsilon_{w} + \varepsilon_{d}} \right)^{1/2} \] (1)
where \( k_0 \) is the wave vector, \( \theta \) is the incident angle, \( G_{m,n} \) is the reciprocal vector of the periodic array (\( m \) and \( n \) are integers), and \( \varepsilon_m \) and \( \varepsilon_d \) are the permittivity of silver and dielectric media (air), respectively. These calculations confirmed the rise of exclusive spectral features at the wavelengths of \( \lambda_1 = 639 \text{ nm} \) and \( \lambda_2 = 716 \text{ nm} \) for the incident angle of 30°. Plotting the magnetic-field distributions at the position of these two wavelengths reveals the origin of these modes (Figures 5d and 5e), in which the vectorial magnetic-field distribution at 639 nm shows a head-to-head behavior, while it demonstrates a head-to-tail behavior at 716 nm. The latter distribution is indeed one of the characteristic signatures of the toroidal dipole mode. The multipole nature of the induced resonances was further analyzed by conducting multipolar decomposition simulations, as shown in Figure 5f. The radiated power from multipoles displayed that the modes at \( \lambda_1 \) and \( \lambda_2 \) are related to the quadrupolar magnetic and toroidal dipole modes, respectively. Finally, the reflectivity of the metasurface was numerically calculated for the incident angle of 30° (see Figure 5g), showing the consistency between the previous predictions for the fundamental wavelengths and reflection response.

The intrinsic merits of both all-dielectric and plasmonic toroidal metasurfaces stem from their capability of robustly confining the incident radiation, from optical wavelengths to THz frequencies. The unique advantages of toroidal resonances have led the rise of a new era in nanophotonics instruments. Ultraprecise immunobiosensors, rapid metaswitches, high-photon yield photodetectors, efficient photonic waveguides, and coherent nonlinear light sources are some of the practical applications of toroidal metasurface technology that have been reported so far. Following, we will review the topical advances in the use of plasmonic and all-dielectric toroidal metasurfaces for designing next-generation optics-based tools. Additionally, as a specific concept, the role of toroidal dipoles in boosting the plexciton dynamics will be pointed out.
3. Photodetection: Enhancing Responsivity Performance

Here, we briefly summarize the possibility of generating photocurrent using toroidal-resonant plasmonic metasurfaces along the IR spectra. In principle, the detection of incident photons using subwavelength plasmonic structures underpins numerous strategic applications, such as spectroscopy, missile warning, light harvesting, nano (bio-) imaging, time-gated distance measurements, and short-distance optical communication.\(^{[109-115]}\) As a leading study,\(^{[82]}\) Ahmadivand and teammates demonstrated how one can harness toroidal plasmonic metasurfaces for narrowband IR light-sensing. This was accomplished by introducing an ordered array of planar metallic meta-atoms on n- or p-doped silicon (Si) substrates, which allowed to probe and evaluate the photoresponse of two different types of photodetectors and enabled studying the influence of free carrier absorption (FCA) in Si substrates.\(^{[116-119]}\) With the help of the induced toroidal dipole mode in the selected bandwidth of the spectrum and utilizing quantitative and qualitative analyses, it is shown that the tailored metaplasmonic structure provides remarkable enhancements for both electromagnetic field confinement and absorption cross-section. The proposed nanoplasmonic meta-atom is depicted in Figure 6a, in which the judiciously defined geometries are specified inside the panel. Under \(\gamma\)-polarized beam exposure, the excitation of toroidal dipole mode (around \(\lambda\sim2850\) nm) was validated both numerically (circles) and experimentally (solid line) (Figure 6b). The SEM images for the fabricated structures are provided as insets. In Figure 6c, the absorption spectra for the plasmonic metasurface is calculated for both types of Si substrates, where distinct absorption is appeared at the position of the toroidal dipole mode. As can be seen in the panel, the extreme IR light absorption feature of p-type Si substrate boosts the absorption spectrum at the toroidal dipole wavelength, giving rise to the generation of large amount of carriers and higher photocurrent in the projected apparatus.

To motivate the design and extract the electrical response of the device, the researchers investigated the carrier generation through applying IR light and bias. Regarding the discussion on operating mechanism of this metasystem, it should be underlined that the strong absorption is due to two important phenomena: 1) excitation of intense and confined plasmons with the formation of a dynamic charge–current configurations and 2) FCA of the p-type Si. Particularly, at the toroidal
dipole position, the substantial field localization provides low emission rate and generation of
dynamic carriers, thus, photocurrent enhancement. The operating principle of the toroidal
photodetection tool has been described based on the theory of hot electron generation in classical
plasmonic systems such as gratings and clusters.\textsuperscript{[110,111,120,121]} Technically, at the magnetic dipole
position ($\lambda \sim 2150$ nm), the field concentration is rational, but, due to limited mean free path (MFP) of
the optically driven electrons in Au, some these electrons moves toward the Au–Si interface.
Assuming that the system maintains an isotropic momentum distribution, more than 50% of the
photoexcited electrons will be lost throughout the process. Conversely, at the toroidal dipole position,
the induced field squeezes within a specific spot and amplifies the localization effect. This provides a
considerable increment in the photogenerated current at the toroidal dipole wavelength. In this limit,
when the energy ($h\nu$) of the photoexcited plasmons becomes sufficiently large, subsequently, the
electrons can attain the required energy to pass the intrinsically formed Schottky barrier and released
into the doped Si, where they are collected as photogenerated current through applied bias.
Theoretically, in a Au/doped-Si nanosystem, damping in the electron–electron scattering increases the
number of excited electrons transferred to the doped substrate.\textsuperscript{[122]} This is followed by an extremely
quick transition of photoexcited electrons into the metallic resonators (from the substrate), which
allows for the accumulation and sweeping of carriers before immediate recombination.

As discussed in this section, the impact of the toroidal dipole mode on the carrier generation was
proved through strong field confinement, and it was verified by computing and measuring the light
detection parameters. In Figures 6d and 6e, the generated photocurrents as a function of the incidence
are illustrated for both doping types of Si substrate. As it was predicted based on the absorption
spectra in Figure 6c, the highest photocurrent is obtained for the p-doped Si-mediated nanodevice,
because of enhanced carrier mobility of the Si substrate, longer lifetime of the photogenerated
carriers, and large amount of electrons at the Schottky barrier. It is important to remark that the
carrier concentration in both doping regimes is set to $2 \times 10^{19}$ cm$^{-3}$. With a gate bias of 0 mV-500 mV,
the photoexcited electrons and holes are drifted to the forward- and reverse-biased electrodes,
respectively. In Figure 6f, numerically computed photoresponsivity values of the toroidal metadevice
are plotted for both doping regimes. Similar to the photocurrent and absorption panels, promising photoresponsivity values, ~14.5 mA W\(^{-1}\) and ~29 mA W\(^{-1}\), are obtained for both types of devices, respectively. Besides, the internal quantum efficiency (IQE) of the metadevice is quantified by considering the ratio between the total number of charge carriers towards photocurrent (\(I_p\)) and the total number of photons absorbed by the structure:

\[
\text{IQE} = \frac{I_p}{q} \left( \frac{S_{\text{abs}}}{h\nu} \right)
\]

where \(q\) is the elementary charge, \(S_{\text{abs}}\) is the absorbed optical power, \(h\) is the Planck’s constant, and \(\nu\) is the frequency of incidence. As represented in Figure 6g, an IQE of 38.5% is attained for the p-type metasystem, while this value drops to ~30% for the n-type photodetector. However, this is not the end of story, and the IQE of the developed metadevice can be further boosted using 2D monolayers, such as graphene sheet\(^{[120,123,124]}\) and MXenes.\(^{[125]}\)

Next, the authors calculated the minimum noise equivalent power (NEP) and detectivity (\(D^*\)) of the NIR photodetector in Figures 6h and 6i, respectively. The minimum NEP of the toroidal plasmonic photodetector is obtained as 5.4 pW Hz\(^{-1/2}\) using:\(^{[126]}\)

\[
i_n = \left( \frac{4k_BT\Delta f}{R} \right)^{1/2}
\]

in which \(k_B\) is Boltzmann’s constant, \(T\) is the room temperature, \(\Delta f\) is the frequency bandwidth, and \(R\) is the resistance of the photodetector. Moreover, the maximum detectivity value of the metadevice is assessed as 7.06 \(\times\) 10\(^9\) Jones via:\(^{[127]}\)

\[
D^* = \mathcal{R} \left( \frac{\Delta}{i_n} \right)^{1/2} / \left( i_n^2 + i_{n,b}^2 \right)^{1/2}
\]

where \(\mathcal{R}\) is the photoresponsivity and \(i_{n,b}\) is the noise current due to background radiation. As another fundamental criterion in photodetector systems, the linear dynamic range (LDR) of the toroidal light sensing tool has been appraised using the following relation:\(^{[128]}\)

\[
\text{LDR} = 10 \log_{10} \left( \frac{P_s}{\text{NEP}} \right)
\]

where \(P_s\) is the saturated power (0.2 µW Hz\(^{-1/2}\)) and the LDR is determined as ~46 dB. The demonstrated toroidal meta-atoms-based photodetector was the first example of its kind. The obtained results for this device explicitly showed how the implemented technology can substantially amplify
4. Nonlinear Lasing: A Deep-Ultraviolet Source

Nonlinear harmonic signal generation from metallic and all-dielectric nanostructures has received great interest in recent years,\(^{129,130}\) due to extreme light confinement capabilities of well-engineered nanophotonic and nanoplasmic metasurfaces.\(^ {130,131}\) Technically, efficient transformation of multiple low-energy photons into a single high-energy photon is known as \textit{harmonic signal generation}, and this concept has been immensely utilized in a wide range of research fields, such as commercial lasing,\(^ {132-135}\) enhanced nano (bio) imaging,\(^{136,137}\) photovoltaics,\(^ {138,139}\) drug delivery,\(^ {140,141}\) nanorulers,\(^ {142}\) beam shaping,\(^ {143,144}\) and military and space sciences.\(^ {145}\) Seeking for an intense nonlinear signal based on second or third harmonic signal generation has triggered researchers to address this fundamental necessity by developing novel optical metasurfaces.\(^ {130-145}\) Such particular methodology is highly important for short wavelength (e.g. ultraviolet (UV)) beam generation,\(^ {81,146-154}\) in which traditional nonlinear crystals reach their limits in terms of transparency and phase-matching between input and output fields.\(^ {155}\)

Among diverse second or third harmonic generation approaches, deep- (\(\lambda=190-280\) nm) and vacuum- (\(\lambda=100-190\) nm) UV (DUV and VUV) signals govern numerous vital applications, including but not limited to photochemistry, extreme-subwavelength scale device fabrication, missile warning, environmental remediation, lasers, and spectroscopy.\(^ {152-155}\) To date, several innovative techniques have been conducted to generate high-gain, coherent, and high-energy UV beam sources, such as Xenon-light sources,\(^ {156}\) excimer lasers,\(^ {157}\) free electron lasers,\(^ {158}\) prism-coupled devices,\(^ {159}\) III-nitride-based light emitting diodes (LEDs),\(^ {160}\) and supercontinuum generation in photonic crystal fibers.\(^ {161}\) Although all of these methods yield intense and coherent DUV and VUV lights, their practical utilization majorly encounters with high complexity, costly fabrication, and limited tunability. As discussed earlier in this section, optical metasurfaces are potential solutions to address these shortcomings. In the nonlinear optics regime, up to now, a large number of all-dielectric and
plasmonic metasurfaces have been tailored to obtain second or third harmonic signals for intensified
UV light production.\cite{145,151} Initial theoretical and experimental studies on UV sources exhibited that
the generation of such shorter wavelengths, particularly in all-dielectric and plasmonic
metastructures, has its own benefits and limitations. While all-dielectric metasurfaces take the
advantage of inherent loss-less optical response, the intensity of the induced nonlinear UV signal
strongly degenerates due to the thickness of the metasurface. On the other hand, intrinsically lossy
plasmonic meta-atoms utilize their strong hotspots and electromagnetic field localization for UV
light generation in subwavelength dimensions.

Newly, researchers have explored idiosyncratic ways to improve the benefits of these
metasurfaces for nonlinear signal generation process, such as engineering much more complex
meta-atoms and designing nanoresonators that are able to confine the incident electromagnetic
within a small spot through inducing toroidal moments, anapole states,\cite{162,163} or Fano resonances.
Among them, lately, toroidal dipole-based plasmonic meta-atoms have been introduced as a reliable
candidate to generate high energy DUV light, nominally five times stronger than that of a
conventional hotspot-enhanced plasmonic nanodimer.\cite{81} The metasurface was structured based on a
periodic combination of Au unit cells on an ITO/glass substrate, in which the metasurface supports
closed-loop charge-current arrangements ($\vec{T}$) between adjacent nanoresonators within a unit cell
(Figure 7a). The geometric values and cross-sectional schematic of the proposed design are indicated
in Figures 7b and 7c, respectively. Here, the ITO sublayer (100 nm) is considered as the nonlinear
material with superior third-order coefficient ($\chi^{(3)}$), while the unit cells serve field enhancement to
amplify the third-order harmonic signal. Figure 7d represents the SEM image of the fabricated 2D
metastructure.

Excitation with $\gamma$-polarized beam generates a pronounced optical resonance close to 785 nm
(Figure 7e). Numerically calculated transmission depicts a reasonable consistency with the
experimentally measured spectra, as the discrepancies most likely due to slight geometric differences.
between the fabricated and devised structures. Following, to capture the origin of the induced resonance, a multipolar decomposition analysis has been conducted (Figure 7f), where the total scattering cross-section of the metasurface has contributions from a toroidal dipole (TD), an electric dipole (ED), a magnetic dipole (MD), and an electric quadrupole (EQ). Here, the dominant mode near the fundamental wavelength can be ascribed to the TD mode (Figure 7f). On the other hand, the charge distribution of the toroidal dipole mode is plotted in Figure 7g, where the electric field is highly confined within the two capacitive openings on both sides, generating antiparallel magnetic moments in proximal resonators. As elucidated in the key principles of flatland meta-atoms, the mismatch between the induced magnetic moments is required to induce charge-current configuration across the metasurface. This configuration forms a substantially localized spinning magnetic field that penetrates into the ITO sublayer, depicted at both fundamental (top) and third harmonic (bottom) wavelengths (Figure 7h).

The generation of third harmonic signal at 262 nm was probed both numerically and experimentally in Figures 7i and 7j, respectively. To validate the advantages of the provided topology in comparison to classical plasmonic systems, the researchers compared the obtained plasmonic response and third-order harmonic signal generation performance with a nanodimer system. Obviously, the nanodimer platform (with a similar fundamental frequency) exhibited much weaker nonlinear harmonic signal response, in spite of applying much higher average pump power. To this end, the intensities were scaled based on the quantified effective third-order susceptibility values. Furthermore, the origin of the nonlinear DUV signal can indeed be attributed to the third-order harmonic signal induced within the metasurface, through FDTD analyses (Figure 7j) and power dependence measurements (Figure 7k). A log-log plot of the nonlinear signal from both structures follows the expected third-order dependence. Conspicuously, the signal intensity obtained from the toroidal metasurface is five times greater than that of the nanodisk-dimer array. Next, a further study to clarify the nonlinear efficiency was performed by calculating the effective third-order susceptibility \( \chi^{(3)}_{eff} \) using the following equation:

\[
\chi^{(3)}_{eff} = \left( \frac{\varepsilon_0 C_n \omega n_2^2}{6 P_{\omega}} \right) \left( \frac{n_\omega n_{2\omega} n_{3\omega}}{P_{\omega}} \right)^{1/2},
\]

where \( \varepsilon_0 \) is the vacuum
permittivity, \( c \) is the speed of light, \( \lambda \) is the wavelength of the fundamental harmonic, \( n_\omega \) and \( n_{3\omega} \) are the refractive indices at the fundamental (\( \lambda = 785 \) nm) and third (\( \lambda_{THG} = 262 \) nm) harmonic frequencies, \( w_0 \) is the beam waist radius, \( l \) is the interaction length, and \( P_\omega \) and \( P_{3\omega} \) are the peak powers at the fundamental and third harmonic, respectively. The calculated \( \chi_{eff}^{(3)} \) of the toroidal metasurface, nanodimer system, and an unpatterned ITO film revealed that \( \chi_{eff}^{(3)} \) (toroid) \( (1.2 \times 10^{-21} \text{ m}^2\text{V}^{-2}) \) is 2.2- and 3.1-times larger than that of the nanodimer and the unpatterned sublayer, respectively. Ultimately, Figure 7I summarizes the effect of the ITO thickness on the generated nonlinear signal intensity. Technically, the thickness of the ITO sublayer specifies the effective refractive index of the metadevice, in which most of the incident light power is coupled into the channel underneath. Here, it should be noted that the excited magnetic hotspots strongly amplify the excitation of the toroidal dipole mode through the spinning charge-current components. Thus, one can anticipate to see substantial confinement of the incident optical beam mostly inside the ITO sublayer, towards enhancing the induced nonlinear harmonic signal.

The presented work clearly corroborated that how carefully structured meta-atoms can give rise to hybrid metallodielectric media for nonlinear signal generation in the high-energy regions of the electromagnetic spectrum. While nonradiative modes, such as Fano resonances and anapoles, provide much stronger nonlinear capabilities, generating these modes at shorter wavelengths with high quality is demanding. However, the toroidal dipole and its unique charge-current characteristics can be induced at the visible regime and maintain strong field squeezing.

5. Toroidal Metasensors: Beyond the Conventional Detection Limits

Photonic and plasmonic metasystems have reinvigorated next-generation and cost-effective label-free biomarker recognition modalities by facilitating strong electromagnetic field confinement down to subwavelength dimensions. They allowed the detection of different sorts of biomolecules (e.g. viruses, enzymes, hormones, envelope proteins, antibiotics, DNA, lipids, organisms, etc.) with high selectivity and sensitivity.\[^{166-172}\] While diverse types of resonant metasensors (e.g. Fano resonant and electromagnetically-induced transparency (EIT) resonant) have been introduced for the detection of
low-weight biological targets, these systems do not efficiently identify ultralow-weight biomolecules at the early-stage of diseases, because of their weak limit of detection (LoD). As an alternative route to the conventional sensor devices, recently, a new class of plasmonic sensors based on toroidal metachip technology has been announced. The unconventional properties of toroidal multipoles have led the rise of advanced biochemical sensors and immunosensors with extraordinary LoD, exceptional figure of merit (FoM), and high precision. Such an interest stems from ulnarrow lineshape, pronounced Q-factor, and high sensitivity to environmental perturbations characteristics of toroidal dipoles:\[179-183\]

\[
\begin{align*}
E_x &= n^2 k_0^3 \left( \frac{1}{r} \times \mathbf{P} \right) \\
E_z &= n^2 k_0^3 \left( \frac{1}{r} \times \mathbf{T} \times \mathbf{r} \right)
\end{align*}
\]  

(3)

where \( \mathbf{P} \) is the vector between the observer and the location of the dipole moment, and \( n \) is the refractive index of the environment. As pointed out in the equation above, trivial alterations in the dielectric permittivity of the media have profound impact on the radiated electric field from the scatterer, which facilitates tailoring precise and highly sensitive plasmonic metasensors.

### 5.1. Toroidal Refractive Index Sensors

In continue, we highlight the recent advances in refractive index sensing and practical biosensing applications based on toroidal metastructures. Gupta et al.\[178\] demonstrated the excitation of a high Q-factor toroidal dipole at THz frequencies and utilized a metasurface design as a refractive index sensor. In Figure 8a, the proposed device is plotted artistically, which includes a multipixel configuration of squares by 15 \( \mu \)m apart from each other. This graph also contains the propagation and illumination direction of the impinging light, as well as the formation of the toroidal spinning charge-current composition. The image of the fabricated metasystem is illustrated in Figure 8b. When a photoresist layer of thickness \( t \) (with \( n \) of 1.66) is spin coated on top of the devised metasensor (Figure 8c), a distinct red shift in the position of the toroidal dipole was observed (Figure 8d). Here, numerically calculated Q-factor of the toroidal mode is quantified as 9.6, which indicates the
rationally sharp linewidth of the resonance. The sensitivity of the metastructure was analyzed depending on the position of toroidal dipole in the presence of thick analyte layers with different refractive indices. **Figure 8e** demonstrates the shift in the position toroidal dipole mode as a function of refractive index. Beyond that, since the frequency shifts in **Figure 8f** seems to be linear, a linear fit can be applied to define the sensitivity of the THz toroidal metasurface, which is 27.3 GHz/RIU (or $4.88 \times 10^4$ nm/RIU).

To explore the effect of the analyte layer and substrate thickness on the performance of the toroidal metasurface, the corresponding sensitivities have been evaluated for different thicknesses of analyte and substrate layers on Si and Mylar substrates. As indicated in **Figure 8g**, the Mylar substrate provides much better sensitivity because of its lower refractive index. Besides, the sensitivity of the toroidal dipole mode is amplified and subsequently saturated with a continuous increment in the thickness of analyte layer. Overall, the maximum sensitivity of the toroidal metasensor is 41 GHz/RIU (or $7.32 \times 10^4$ nm/RIU) for the Si substrate and 186 GHz/RIU (or $10.3 \times 10^4$ nm/RIU) for the Mylar substrate, where the sensitivity curve in **Figure 8g** is almost saturated beyond 13 µm thick analyte layer. As a final point, to examine the impact of the substrate thickness on the sensitivity of the toroidal platform, full-wave numerical analyses have been executed for 4 µm analyte covered metamolecule on different thicknesses of Si and Mylar substrates. The results of these studies are depicted in **Figure 8h**, where the sensitivity of the sensor reduces exponentially with an increase in the thickness of substrate and eventually saturates beyond 20 µm.

While toroidal plasmonic metasurfaces provide high precision refractive index sensing, all-dielectric metasurfaces are also reliable platforms for this purpose. The stored electromagnetic energy at the resonance and high-index particles (or structures), with much higher refractive index than the environment, enable the excitation of ultrahigh $Q$-factor and low-loss resonant lineshapes with substantial sensitivity to the permittivity variations of the media.\textsuperscript{[184,185]} Recently, Chen et al.\textsuperscript{[186]} inspected the possibility of environmental refractive index sensing using all-dielectric toroidal metasurfaces in the THz frequencies. By tailoring a four-member antisymmetric cluster composed of...
LiTaO$_3$ microdisks (Figure 8i) and exploiting the robust polaritonic response of this compound, they successfully induced ultranarrow toroidal dipole around 2.5 THz (Figure 8j). This panel also comprises variations in the transmission spectra due to perturbations in the refractive index of the surrounding. Clearly, the toroidal lineshape continuously red-shifts with the increase in the refractive index of the combined microfluidic channel. For instance, going from $n=1$ to $n=1.8$, the resonance frequency shifts from 174.3 GHz to 334.9 GHz. Figure 8k illustrates the displacement in the toroidal dipole position as a function of refractive index perturbations, and as it is apparent, the frequency shift linearly rises with the increase in the environmental refractive index. Moreover, the sensitivity of the all-dielectric metasurface was determined by quantifying the slope of the linear fitting function of the frequency shift. To this end, the linear function can be defined as: $y=-448.7+438n$, in which $y$ is the parameter for the frequency shift. This resulted in the sensitivity of 438 GHz/RIU. As a proof of concept, the influence of analyte’s thickness on the all-dielectric metasensor’s response has been evaluated. The obtained results for the analyte with $n=1.6$ and varying thickness are presented in Figure 8l. In this set of investigations, the frequency shift increases monotonically and then saturates at 263.5 GHz for the thickness around 10 μm. Subsequently, the researchers computed the FoM of the sensor for refractive index perturbations and it is shown that the FoM decreases from 515 to 31 with the increase in the refractive index of the environment.

So far, we have discussed the properties of diverse types of toroidal biochemical sensor devices based on quasi-infinite metasurfaces. Following that, the possibility of the integration of microfluidic channels with toroidal metasensors was studied numerically by Chen et al.\textsuperscript{187} This understanding showed that the flow microchannel-based miniaturized THz metaplatform can be tailored to detect non-polar and polar fluids. The schematic diagram of the THz toroidal biochemical sensor combined with the microfluidic channel (sealed by quartz lid) is sketched in Figure 8m. The insets are the top-view of the designed aluminum unit cell (top image), where the optimized geometries are provided in the caption, and the cross-sectional view of the metasensor in $yz$-plane, where the analyte is filled in microfluidic channel (bottom image). For a fixed microchannel height (8 µm), the transmission spectra in Figure 8n displays the sensor response for different refractive index of analytes.
Noticeably, the sharp resonant dip monotonously red-shifts from $n=1.0$ to 1.8, with the total shift of 0.414 THz. In addition, the authors examined the influence of microfluidic channel height on the resonance frequency shift (when $n=1.6$), as presented in Figure 8. By increasing the channel height, the position of the toroidal resonance red-shifts and saturates at 8 µm. This implies that continuous increase in the microchannel height does not affects the frequency shift. Therefore, the red-shift of the toroidal dipole mode is mainly because of the presence of analyte within the capacitive openings, which modifies the capacitance of metasurface and eventually changes the resonance frequency position. The FoM analysis is plotted in Figure 8p; by going from $n=1.0$ to $n=1.8$, the FoM decreases from 240 to 144. Besides, the numerical results revealed that substantial resonance shifts and sensitivity values (i.e. 521.6 GHz/RIU and 37.88 GHz/RIU) can be achievable for non-polar and polar liquids. Although the extracted results in all deliberated studies look promising, the need for metasensors with much higher precision in practical assesses, with the ability to be employed in commercial and modern clinical tools, has directed scholars to improve the sensing properties of toroidal metasensors by conducting innovative approaches and structuring complex platforms with high $Q$-factor resonances.

### 5.2. Toroidal Immunosensors

Beyond these studies, toroidal metastructures have also been employed for practical immuno-sensing applications with ultrahigh sensitivity and excellent LoD at very low densities.\cite{84-87} Here, we highlighted a very recent study on implementing a plasmonic MIR toroidal metasensor with substantial immuno-sensing performance. In this work,\cite{87} researchers established quick and precise detection of antibiotic molecules (~0.6 KDa) at attomolar (aM) levels, with the help of unique sensitivity characteristics of the designated toroidal plasmonic meta-atoms. In general, the MIR spectrum encircles vibrational modes of many biological objects, including but not limited to envelope proteins, DNA, and lipids.\cite{185} Even if the amplitude of these vibrational modes are inherently low, as a popular modality in accessing their fingerprints, MIR spectroscopy provides non-invasive, non-poisonous, and non-destructive label-free biosensing.\cite{188,189} In Figure 9a, an artistic
schematic of the proposed meta-atom in the presence of Kantrex molecules is illustrated (inset is the molecular structure of kanamycin sulfate). The SEM image of the fabricated arrays is shown in Figure 9b. The transmission spectra for both experimental measurements and numerical calculations under y-polarized illumination are demonstrated in Figure 9c, confirming the excitation of a toroidal dipole mode at \( \lambda \approx 5250 \) nm \( (\omega \approx 1904.7 \) cm\(^{-1}\)). Contrarily, for the x-polarized incident light, this mode vanishes due to missing discrepancy between the direction of induced magnetic moments and surface current densities in nearby resonators.

Next, the researchers employed Kantrex antibiotic molecules by considering different concentrations to estimate the sensing capability of the toroidal metasensor. To this end, the detection of the antibiotic molecules is conducted through the transmission difference between two different regimes (i.e. in the absence and presence of biomolecules):

\[
\Delta T(\omega) \equiv |t_{yy}^{\text{Water}}(\omega)|^2 - |t_{yy}^{\text{Molecule}}(\omega)|^2,
\]

in which \( t_{yy} \) is a tensor correlating with the transmitted and incident electric fields under y-polarized illumination. By introducing 10 µL of antibiotic solution to the plasmonic metasurface (Figure 9d), it is shown that the accumulation of Kantrex molecules at the capacitive openings affects the measured transmission spectra. Considering water as reference, a significant red-shift is observed for the toroidal dipole mode within the range of 5400 nm < \( \lambda_T < 6600 \) nm \( (1515.1 \) cm\(^{-1}\) < \( \omega_T < 1851.8 \) cm\(^{-1}\)), as the concentration of the Kantrex molecules is continually increased from 0.1 fM to 10 fM (Figure 9e). Figure 9f exhibits the toroidal dipole shift versus the concentration of the Kantrex molecules, in which the slope of the resonance shifts is noticeably sharp from 0.1 fM to 10 fM (shaded area by green hue), verifies the LoD of around ~0.85 fM (or 850 aM). This behavior was also perceived for much denser concentrations with a moderate slope (shaded area by red hue), because of the destructive impact on the formation of the toroidal dipole moment. To explore the origin of the observed resonance shift, one should consider both permittivity modifications and near-field coupling during the theoretical calculations as: \cite{190}. 

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where \( t \) is the thickness of the liquid layer, \( \varepsilon \) is the permittivity, and \( |E_y(r)| \) is the near-field at the gaps. Here, it should be underlined that to introduce the Kantrex molecules to the system \( n=1.67 \) was employed, and the approximate thickness of the dispersed layer of molecules (\( \sim 5.8 \) nm) was defined using ellipsometric data. The experimental results for before and after binding conditions are plotted in Figure 9g, representing the variations in the transmissivity ratio (\( \Delta T/T \)) of the toroidal dipole moment. This work and other recent studies based on the use of toroidal metaplatforms for biosensing and immunosensing purposes revealed that how extremely localized field confinement in the subsequent unit cells can lead to highly precise detection of low-weight molecules at extremely low-level concentrations (e.g. aM, fM).

6. Active Hybrid Toroidal Metamodulators

There have been immense efforts in the metasurface technology throughout the past decade by focusing on the possibility of realizing dynamic functionalities, such as active modulation of electromagnetic radiations.[8,191-194] The integration of smart and multifunctional compounds with metaphotonic and metasplasmonic systems have granted new opportunities to tailor next-generation subwavelength all-optical and optoelectronic instruments, including but not limited to active filters, transducers, and modulators.[195-197] As a conventional approach, gated 2D monolayers (e.g. graphene,[198-202] semiconducting transition metal dichalcogenide (TMDC) monolayers,[203-206] MoS\(_2\), MoSe\(_2\), WS\(_2\), WSe\(_2\), and low-dimensional materials[207,208]) have widely been employed to enhance the functionality of metadevices ranging from IR to THz frequencies. Instead, an active control over the spectral response of optical metasurfaces can be realized via thermally reversible phase-change materials (PCMs) (e.g. VO\(_2\),[209-212] Ge\(_2\)Sb\(_2\)Te\(_5\),[213-218] and AgInSbTe\(_2\).[219,220]) This concept relies on the active toggling between amorphous and crystalline states of the PCM at specific temperatures,[221] which enables the development of functional photonic tools across a broad range of frequencies.
Furthermore, functional plasmonic nanocomposites (that are operating based on the reversible changes in dielectric matrix’s refractive index) have also been introduced as a promising substitute for classically tunable substances. All these modalities allowed for optimizing the performance of various photonic and plasmonic metamodulators. Below, we present the recent advancements that have been conducted toward improving the functionality of planar toroidal metadevices.

### 6.1. Functional Toroidal Metamodulators Based on Phase-Transition Compounds

Recently, Gupta et al.[224] performed a detailed study to induce toroidal dipole moment in metasurfaces combined with ultrathin Si layers. It is shown that such sublayers, underneath the capacitive gap areas of the metallic unit cells, dynamically control the optical properties of the entire hybrid toroidal metasurface through applied NIR femtosecond pulses. Figure 10a illustrates a microscope image of the fabricated metaswitch composed of two-member unit cells in periodic arrays. The magnified microscope image of the meta-atom is depicted in Figure 10b, where the geometric parameters are specified. The excitation mechanism of the toroidal dipole is artistically displayed in Figure 10c, where the researchers utilized this system to devise a photoswitch. Theoretically, this was accomplished by suppressing the induced electromagnetic response of one or both resonators in a mirrored configuration, in which the dynamic transition among toroidal, magnetic, and electric dipoles became conceivable. Such an active tuning provided a smooth evolution of the toroidal resonance depending on the on/off state of the pump fluence. Regarding modulation depth (MD) quantification, Figure 10d represents the percentage variations in experimentally obtained transmission amplitude for different pump fluence values. Remarkably, the change in the corresponding amplitude is significantly larger at 0.545 THz, in comparison to that of at 0.453 THz. Besides, the extracted peak-to-peak amplitude MD between the toroidal resonance lineshape (blue shaded area) and the corresponding transmission peak (gray shaded region) is ~73%.

Numerical studies have also been conducted for further verification of the switching performance. It is demonstrated that the electromagnetic response of the metasurface can be switched between toroidal dipole and magnetic dipole by controlling the direction of induced magnetic moments with...
respect to each other. **Figure 10** illustrates the simulated transmission spectra in the presence of Si subpads. It should be noted that, these subpads are placed below the capacitive split gaps of only one pixel in the mirrored design. As the conductivity of Si ($\sigma_{\text{Si}}$) rises, the amplitude of the toroidal dipole resonance reduces until $\sigma_{\text{Si}}$ reaching a value of 1200 S/m. Going beyond this point excites the magnetic dipole mode around 0.4 THz. Overall, the proposed approach is a potential technique to create toroidal resonance-based active metadevices and narrowband filters in the THz frequency regime.

Apart from the above study, there is an ongoing race to enhance the performance of metaswitches using toroidal metasurfaces.\[^{75,78,225}\] Specifically, at the telecommunication bandwidth, the toroidal metasurface concept has addressed some of the current limitations (e.g. MD, insertion loss) of traditional optical metaswitches. As discussed earlier in this section, optothermally tunable compounds (e.g. PCMs) have an undeniable role in improving the functionality of optical devices. In light of these, Ahmadivand *et al.*\[^{226}\] have developed a multicomponent metasurface composed of three nanopixels to excite resonant modes at the NIR region. Here, going beyond the conventional plasmonic nanoresonators, they presented a novel metallodielectric meta-atom, based on a blend of metallic and PCM parts, to support both Fano and toroidal dipole resonances depending on the state of the PCM (specifically, Ge$_2$Sb$_2$Te$_5$ or GST). Taking advantage of the reversible switching feature of GST, they quantitatively demonstrated that the excitation of different modes is possible without requiring any morphological changes in the unit cell. Using full-wave electromagnetic computations, it is proved that a judicious mix of metallic and GST components yields an active toggling between Fano and toroidal dipole modes, by changing the direction of induced magnetic dipole moments. It was also claimed that the proposed metastructure provides rapid and efficient NIR switching with high MD for practical telecommunication applications.

**Figures 10f** and **10g** represent the transmission spectra of two different planar plasmonic unit cells under $\gamma$-polarized illumination. These two panels are given to demonstrate the formation of Fano and toroidal dipole modes in a similar system with minor geometric alterations. As depicted in these
graphs, the unit cell with unbroken peripheral nanorings acts as a Fano-resonant nanostructure (Figure 10f), while removing the specific arcs of nanorings leads to the excitation of a completely different spectral feature, or namely the toroidal mode (Figure 10g). The reason behind the formation of different modes can be explained by considering the behavior of rotating surface currents in satellite nanorings. Considering Fano-resonant structures and plasmon hybridization theory, when two nanorings are located closely with a rectangle resonator in between, the nanorings possess dark magnetic dipole (m) modes, which can couple to the bright electric mode induced by the rectangle resonator. As indicated in Figure 10f, the direction of the formed magnetic dipole moments and excited charges follow a similar trend with respect to each other. Conversely, for the unit cell with homogenously removed arcs from the surrounding nanorings (Figure 10g), the Fano dip vanishes and the toroidal minimum appears owing to the formation of magnetic dipole moments in opposite directions.

While having both Fano and toroidal resonances on the same platform (through geometrical alterations) paves the path of designing advanced nanoscale devices, such a blueprint is subject to the lack of active tunability. To address this impediment, researchers introduced a PCM (here GST) into the gap areas (arcs) of the nanorings, which yields an active control over the two distinctly different resonant modes. Figure 10h shows an artistic illustration of the meta-atom in the presence of GST, as a metallodielectric planar unit cell. For the amorphous phase of GST (a-GST), the arc behaves as a dielectric material, and owing to the dominant characteristic of capacitive coupling, one can anticipate to see the formation of a toroidal dipole mode as well as a weak magnetic dipole mode at lower energies. On the other hand, for the crystalline phase of GST (c-GST), the entire structure behaves similar to the Fano-resonant regime, hence, the evolution of a pronounced Fano dip is observed. Using the extracted data and careful selection of the meta-atom’s dimensions, the transmission amplitude of the devised active telecommunication switch is provided in Figure 10i. As it is clear, the GST arcs enable supporting a toroidal dipole at 1550 nm, when it is in the amorphous state (OFF). Conversely, when the GST are in the crystalline state (ON), a Fano dip emerges around 1850 nm. Ultimately, in this study, using the rapid and non-volatile phase toggling ability of GST, a useful
methodology for developing actively tunable plasmonic metasurfaces for practical telecommunication applications is demonstrated.

6.2. Functional Toroidal Metamodulators Based on Gated Monolayers

As it was discussed at the beginning of this section, the integration of plasmonic or photonic meta-atoms with optoelectronically tunable atomic sheets have broadly been employed to develop functional metadevices.\textsuperscript{[198-202,207,208]} Aforementioned works have demonstrated that the interaction between, for example, the graphene monolayer and plasmonic meta-atoms is a reliable approach to actively manipulate the spectral properties of the entire metasystem by changing the Fermi energy level of the atomic carbon sheet.\textsuperscript{[229-232]} Pioneering efforts in the use of 2D graphene sheet coupled to a toroidal metasurface date back to couple of years ago by focusing only on its numerical aspects.\textsuperscript{[101,233]}

Driven by the ongoing race to experimentally observe tunable toroidal modes, the possibility of inducing toroidal dipole mode and electro-optical tuning of this spectral phenomenon in the THz spectra has recently been realized.\textsuperscript{[234]} As a well-known fact in nanophotonics, an atomically thin graphene sheet ($<\lambda/10^6$) facilitates efficient control over the interactions between incident radiation and graphene through its gate-controllable electronic features. In principle, the optical functionality of graphene emanates from the Pauli blocking of interband transitions.\textsuperscript{[235,236]} At the charge neutrality point, these transitions yield to the global absorption of graphene at any wavelength. In fact, applying bias to the graphene layer blocks some of these interband transitions, and the absorption of the 2D monolayer exhibits step-like performance around the interband threshold, which can be defined through the Fermi energy.\textsuperscript{[237,238]} In addition, the photoconductivity of this monolayer can be modified by altering the carrier concentration via applied voltage, photodoping, or chemical doping. This has successfully been attained by modeling the electronic characteristics of graphene sheets in terms of massless Dirac fermions.\textsuperscript{[232,239,240]}

Using the mentioned properties of gated graphene and tuning its Fermi energy level, Chen et al.\textsuperscript{[101]} numerically probed the coupling between graphene layer and metallic unit cell by showing the excitation of functional toroidal dipole mode in the THz spectra. Figure 11a shows a schematic
diagram of the tailored planar metamolecule, where the incident THz wave polarized along the x-axis direction. The transmission spectra of the induced toroidal dipole mode is plotted in Figure 11b, indicating a dip around 1.744 THz in the absence of graphene monolayer. To further verify the formation of the toroidal dipole, electric and magnetic field distributions, and associated surface current density of the meta-atom is computed and portrayed in Figures 11c and 11d. Obviously, the induced magnetic moments in each side of the unit cell point out opposite directions and this mismatch initiates the head-to-tail charge-current configuration. Next, to model the coupling between graphene and toroidal metamolecule, the optical properties of the metasystem is defined by considering the complex surface conductivity, in which both intraband and interband transitions must be involved. By neglecting the contribution of the interband transitions in the THz regime, the dominant intraband conductivity can be formulated as:

\[ \sigma_{\text{intra}} = ie^2E_f/\pi\hbar^2(\omega + i\tau^{-1}) \]

where \( E_f \) is the Fermi energy, \( \hbar \) is the reduced Planck’s constant, and \( \tau \) is the relaxation time defined as:

\[ \tau = \mu E_f/(e\nu_f) \]

in which \( \nu_f \) is the Fermi velocity as \( \approx 10^6 \) m/s and \( \mu \) is the carrier mobility as \( 10^4 \) cm\(^2\)V\(^{-1}\)s\(^{-1}\). Besides, the permittivity of graphene layer is computed using \( \varepsilon_g = 1 + i\sigma_{\text{intra}}/\omega\tau_g \). Given that the graphene layer majorly impacts the capacitive coupling areas by short-circuiting them, therefore, by placing it on top of the metastructure, the toroidal dipole mode experiences a dramatic modification in resonance strength, while the electric field strength suppresses because of the recombination effect at the two ends of the central split gap. In Figure 11e, the transmission spectra represents the influence of the Fermi energy on the amplitude of the toroidal dipole mode. When \( E_f = 10 \) meV, the resonance and electric field strength decreases in comparison to the bare metasurface, as plotted in Figure 11f. By further increasing the Fermi energy, the strength of the toroidal resonance and electric field in the central gap become dramatically weak. As the Fermi energy increases up to 40 meV, the strength of both toroidal resonance and electric field disappears, implying switching off the toroidal dipole mode, and the central capacitive opening is shorted entirely by the graphene overlayer. Consequently, the proposed planar metasurface acts as an active THz modulator. Throughout this process, the resonance frequency is slightly shifted from 1.745 THz to 1.756 THz, because of the minor alterations in \( E_f \). Lastly, the largest variation in the transmission amplitude (\( \Delta T \)) was reported as...
63.2%, revealing the potential of the designed THz metasurface for functional modulation applications.

In continue, similar to the presented study above, Liu et al. designed a high-performance NIR toroidal metamodulator by combining an all-dielectric metasurface with graphene (Figure 11g). Under transverse polarization illumination, numerical investigations confirmed the excitation of the toroidal dipole mode with a $Q$-factor up to 1702 (Figure 11h, no layer panel). To analyze the performance of the metamodulator, the transmission spectra of the system in the presence of graphene layer (with the Fermi energies of 0.6 eV, 0.5 eV, and 0.4 eV) were obtained numerically (Figures 11h). Compared to the optical response of the dielectric metasurface, the dip in the transmission plot changes slightly when the graphene layer with $E_F = 0.6$ eV is considered, as the resonance bandwidth is broadened with the decrease in the Fermi energy and eventually, the spectral contrast ratio is drastically reduced. Thus, the devised 2D metamaterial can be used as an active optical modulator by tuning the intrinsic properties of the graphene monolayer. To explore the underlying mechanism, the distributions of the displacement current density $|J|$ in the absence and presence of graphene monolayer are probed and illustrated in Figure 11i. Numerical analyses demonstrated that the transmission amplitude of the toroidal dipole mode can be effectively modified by altering $E_F$ of graphene, and the maximum transmission coefficient difference (MD) up to 78% can been achieved.

7. Toroidal photonic waveguides

The transportation of electromagnetic energy below the diffraction limit through near-field coupling between proximally spaced subwavelength resonators have led to the emergence of optical waveguides. Within the last 20 years, both photonic and plasmonic waveguides have extensively been studied and modeled theoretically using different approaches, including but not limited to extended Mie theory, multipole modules, numerical simulation tools, and point dipole models. From the practical perspective, optical waveguides possess broad range of strategic applications in advanced telecommunication systems, sensing instruments, lasers, and integrated nanophotonic circuits. Conventionally, both plasmonic and photonic waveguides
have been designed based on ordered arrays of subwavelength resonators.\cite{258-262} However, the need for more efficient and low-loss waveguides enabled the rise of “metasurface-loaded waveguides”.\cite{263-266} In general, quasi-infinite metasurfaces, as the subwavelength resonant scatterers, can be devised to control the propagation of the optical power. To enhance the decay-length of guided waves and to reduce the inherent losses in optical systems, metasurface-loaded waveguides based on all-dielectric resonators have been acknowledged as promising candidates for waveguiding purposes. Historically, the research in this field was mainly focused on the telecommunication bands across the NIR region. However, the need for waveguides to operate at THz and microwave frequencies has triggered researchers to rescale the optically-resonant metasurface-loaded waveguides to support pronounced resonances at longer wavelengths. Recently, noteworthy solutions have been introduced for this purpose,\cite{267-270} and among them, the use of all-dielectric toroidal metasurfaces was presented for the first time by Zografopoulos.\cite{270} The schematic representation of the metasurface is illustrated in Figure 12a, in which the dielectric cuboids are designed with specific periodicity (p) and geometries to support the toroidal dipole mode along the microwave frequencies. The panel in Figure 12b contains the cross-sectional scattering profiles of the magnetic dipole (md), electric dipole (ed), magnetic quadrupole (mq), electric quadrupole (eq), Cartesian electric (p), and toroidal (t) dipoles for \( h=3.2 \) mm. This panel also shows the excitation of a distinct toroidal lineshape around \( f_a=10.57 \) GHz (see the inset in Figure 12b). The provided scattering profile can be written as:

\[
C_{scat}^{tot} = \int \mathbf{n} \cdot \mathbf{P}_{scat} dS
\]

where \( \mathbf{P}_{scat} \) is the Poynting vector of the scattered field, \( \mathbf{n} \) is the normal vector, and \( \mathbf{P}_{in} \) can be defined by: \( \mathbf{P}_{in}=n_p/2Z_0 \), in which \( n_p \) is the refractive index of the environment and \( Z_0 \) is the impedance of vacuum. Besides, the numerically calculated \( x-y \) cross-sectional profile of the electric near-field in Figure 12c explicitly indicates a double loop of opposite circular displacement currents, as an intrinsic feature of a dynamic anapole mode.\cite{271,272} It should be underlined that although the anapole mode yields to zero far-field radiation, the total scattering cross-section is indeed not zero, since there are minor contributions from other multipole moments (e.g. magnetic dipole moment). To study the
electromagnetic response of the metasurface for \( h=3.2 \text{ mm} \), \( y \)-polarized plane wave was employed, and the corresponding transmission and reflection spectra are provided in Figure 12d. As indicated, a sharp peak (dip) in reflectance (transmittance) at 10.4 GHz is observed. It is also shown that the interference between the induced moments and their collective oscillations give rise to different Fano lineshapes. Next, the radiated power distribution of the metasurface for the considered multipoles is depicted in Figure 12c, which allows us to understand the origin of the induced resonance. This panel reveals a strong electric dipole contribution, due to the excitation of toroidal dipole mode, and a noticeable magnetic quadrupole contribution, while all other multipoles are dramatically suppressed.

The tailored toroidal metasurfaces have been utilized in different alignments to design parallel-plate and rectangular photonic microwave waveguides. Figures 12f and 12g exhibit the schematic representations of both ideal parallel-plate waveguide (formed between perfect electrical conductor (PEC) sheets) and more realistic parallel-plate waveguide (formed between copper sheets with a low-permittivity and low-loss foam with the permittivity of \( e_{r,b}=1.046-i0.0017782 \)).[271] Practically, the latter parallel-plate waveguide platform is more realistic (where the conductivity of the copper boundaries is set to \( 5.81 \times 10^7 \text{ S/m} \)), therefore, considering two ports for the transverse-electric mode (TEM), the input port is excited and the \( S \)-parameters of the system (\( S_{11} \) and \( S_{21} \)) are numerically calculated for a waveguide with \( L=40 \text{ mm} \). To this end, the power transmittance and reflectance of the waveguides are computed as \( T=|S_{21}|^2 \) and as \( R=|S_{11}|^2 \), respectively. In Figure 12h, the power transmittance, reflectance, and loss spectra of the realistic parallel-plate waveguide and the cuboids of \( w=8 \text{ mm} \) and \( h=3.2 \text{ mm} \) for different pitch size conditions are presented. By evaluating the results with the ones for the equivalent metasurfaces, it is shown that for \( p=w \), the cuboid array leads to a Fabry-Pérot response where the multipole modes manifest. Conversely, in all other regimes (\( p \neq w \)), the toroidal dipole mode is excited. The results verify that the shorter pitch values yield to higher field enhancement in both the cuboid volume and the spacing between the cuboids and the copper walls. Although the induced toroidal resonance is sharper, it possesses dramatical losses. In the case of metasurfaces, these losses are mainly originated from the absorption in the cuboid, whilst in the case of waveguide, they are due to additional conduction losses at the copper metallic surfaces and
absorption in the foam. In continue, by increasing the size of the pitch, the field enhancement at the copper surface is decreased, therefore the conduction losses are relaxed.

While the parallel-plate waveguide seems as an idealized platform for electromagnetic wave propagation at microwave frequencies, practically, the parallel-plate waveguide of Figure 12g has to be ended at the lateral walls. Theoretically, a perfect magnetic conductor (PMC) boundary condition would maintain the symmetries of the structure; however, PMC materials cannot be found in nature. To solve this problem, one can terminate the waveguide with metallic or quasi-PEC walls (Figure 12i). Here, the width of the waveguide was defined in such a way that it provides a finite number \((n)\) of meta-atoms of the alike metasurface \((W = n.p)\). The new design corresponds to a traditional microwave rectangular waveguide, with a stripe of \(n\) cuboids placed normal to the rectangular waveguide axis, in which the fundamental TE\(_{10}\) mode propagates at frequencies higher than the cut of frequency \((f_c=\nu/2W, \text{ where } \nu=\nu/b \text{ and } n_b \text{ is the refractive index of the filling substance})\). As a well-known fact, standard microwave rectangular photonic waveguides can be devised to operate in the single-mode regime \((1.25f_c<f<1.89f_c)\). This bandwidth is targeted so that the operating frequency is larger than \(f_c\) to limit possible losses and dispersion, but also below the cutoff of the next high-order mode. In terms of geometrical properties, a proper design would be a substrate integrated waveguide. In this limit, the fundamental mode can be in- and out-coupled to the low-profile and close-packed configurations. For instance, such a structure can be performed using slot arrays on top of a beam-forming network, as recently realized in the design and fabrication of substrate integrated waveguide metasurface-based leaky-wave antennas.\(^{[272-274]}\) The spectra in Figure 12j illustrates the transmittance of a 40-mm long rectangular waveguide with various lateral width and periodicity arrangements. The results demonstrate that the rectangular waveguide acts identically to the benchmark parallel-plate waveguide, with the exception of a resonance around 8.95 GHz. This corresponds to a resonant feature excited by the quasi-PEC lateral boundary conditions, as verified with the electric field profiles of Figure 12k. Besides, it interacts with the slightly changed reflectance/transmittance spectrum of the cuboid array and gives rise to the formation of a Fano lineshape. Beyond that, the
photonic metasurface-induced toroidal mode around 10.4 GHz still exists, as validated in Figures 12j and 12k, respectively.

8. Toroidal Metasurfaces for Manipulation of Electromagnetic Polarization

Polarization is one of the main characteristics of electromagnetic waves, carrying important knowledge in signal transmission and assessment. In connection with this, manipulation of electromagnetic polarization maintains a significant impact on various field of studies, ranging from user products to technological applications.\cite{275-277} Traditionally, total internal reflection effects in crystals and polymers have been utilized for the purpose of polarization conversion.\cite{277,278} This process, in practice, gives rise to phase retardation among the two orthogonally polarized wave components. However, the efficiency and bandwidth of this technique is limited and requires complicated designs using multilayered films or Fresnel rhombs.\cite{279} These weaknesses have successfully been addressed by the use of bulky artificial media at microwave frequencies, in which the polarization conversion was obtained by designing resonant unit cells that exhibit birefringence.\cite{277,280,281} Later, with the development of planar metastructures based on flatland optics, wideband and multifunctional control of polarization and gain were accomplished.\cite{282-286} Among them, the promise of toroidal metasurfaces in diverse applied directions has motivated researchers to employ these architectures for controlling the polarization of electromagnetic radiations (e.g. linear polarization conversion\cite{287,288} and circular cross-polarization conversion\cite{289,290}).

In this context, using all-dielectric toroidal-resonant metasurfaces that operate at W-band and THz frequencies, Algorri et al.\cite{288} showed that structured antisymmetric unit cells based on high-index particles can be utilized as birefringent metasurfaces, which affects the polarization of incidence. Initially, it is assumed that the platform is symmetric and composed of periodically configured dielectric (Si) disks (Figure 13a). The transmission and reflection spectra are illustrated in Figure 13b, verifying the excitation of a toroidal dipole along the W-band (75-110 GHz). In this regime, a resonant phase variation of 180° is created (Figure 13c). Taking advantage of such a phase change in the entirely symmetric structure, novel devices for polarization control can be tailored, such as
polarizing beam splitters. Besides, it is discovered that breaking the symmetry of Si resonators allows to build a polarization converter device. To that end, by assuming that the response of the converter is based on linearly polarized incident, therefore, such polarization must be oriented 45° with respect to the $x$-plane. This polarization would be disintegrated into two perpendicular components that are phase shifted with different angles (Figure 13d). By altering the geometry of meta-atoms along one axis, the polarization components can be phase shifted with different orders. In this limit, one can expect a 180° phase retardation between the modes, which rotates the polarization from 45° to -45°. This results in an orthogonal polarization conversion (Figure 13e). It should be underlined that the metadevice can also be constructed in such a way that to generate other retardations, such as shifting linearly polarized beam into circularly polarized light and vice versa and generation of elliptical polarization. Lastly, the reflection amplitudes of these two curves are analogous to a distinct difference in phase between $x$- and $y$-polarized modes (Figure 13f).

To explore novel devices in this concept, we probe the properties of a circular polarizer, as another type of light controlling device that has been developed based on diverse forms of artificial media, which can be assorted in single-band, dual-band, and broadband classes. With the rise of toroidal resonances, high-performance reconfigurable instruments to control the polarization of light have become popular. Among them, latterly, Jing et al. utilized the Kirigami concept to conceive a novel type of metamaterial whose electromagnetic characteristics would be converted from nonchiral to chiral and vice versa at single-band, dualband, and broadband frequencies through stretching the arrays of toroidal-resonant metamolecules. They used periodic arrays of split-ring resonators on foldable sheets. By converting the metasurface into a 3D Kirigami-based metamaterial, the resonant modes possess a progressively enriched chiroptical behavior. For this purpose, two types of Kirigami metamaterials were engineered based on four split-ring resonators: Type-I represents Kirigami structures whose nearby resonators are linked by the midpoints of the sides at the cut boundary, and Type-II are based on buckling-induced Kirigami where the unit cells are connected through the vertices of the squares (Figure 14a). Particularly, all Kirigami metamaterials can be folded into two styles of chiral enantiomers, which are mirror images of each other. On the other hand, to induce the
toroidal dipole mode, Type-III Kirigami metamaterials were created by combining two Type-I layers, where the mirror symmetry is broken (Figure 14a).

Considering the optical properties of the developed folding metamaterials, the Type-I structure exhibits chiroptical responses at 6.78 GHz when $\theta = 45^\circ$, with opposite handedness (Figures 14b and 14c). For the L-handed enantiomer, a L-handed resonant feature was observed, where the R-handed circularly polarized waves are mostly transmitted and L-handed circularly polarized waves are perfectly reflected. For the Type-II structure, bending is applied to generate out-of-plane rotations, where the corresponding spectral results are plotted Figures 14e and 14f. Obviously, an additional chiral resonant mode arises at 7.8 GHz with opposed handedness. When linearly polarized light interacts with the L-handed Type-II structure, left- and right-handed circularly polarized waves are transmitted at 6.78 and 7.8 GHz, respectively. Similar to the previous regime, the R-handed structure controls the waves with opposite handedness. Thus, the Type-II metamaterial acts as a bifunctional circular polarizer that filters different spin states at two resonant wavelengths. The Type-III platform is stacked from a pair of Type-I metamaterials with equal handedness. The panel in Figure 14h illustrates the excitation of two resonant features of the L-handed Type-III at 6.40 GHz and 7.12 GHz. In contrast, stacking a pair of R-handed Type-I metamaterials produces an R-handed Type-III metastructure that performs oppositely. Furthermore, the circular dichroism analysis ($\text{CD} = |t_{RR}|^2 - |t_{LL}|^2$) allows to prove the exquisite capabilities of the Kirigami metamaterials as reliable circular polarizers. The corresponding circular dichroism (CD) curves for three different states ($\theta = 0^\circ, 45^\circ, -45^\circ$) of Kirigami metamaterials are represented in Figures 14d, 14g, and 14j. Clearly, when $\theta = 45^\circ$, the highest CD for Type-I, Type-II, and Type-III metaplatforms are 0.90, 0.89, and 0.94, respectively. This intriguing performance makes Kirigami-based metastructures as a promising competitor for conventional reconfigurable circular polarizers.

9. **Plexciton Dynamics: Intensifying Strong Coupling in Subwavelength Regime**

Strong plasmon-exciton interactions in subwavelength structures have received ample interest towards analyzing light-matter interactions through diverse sorts of approaches, including but not limited to strong coupling in hybridized platforms, Fano interfering, and plasmon-enhanced emission and absorption. Generally, the tight electromagnetic field confinement at extreme-subwavelength...
dimensions have enabled robust destructive and constructive interferences, yielding generation of new spectral features.\textsuperscript{299,304} Vacuum Rabi oscillation is one the most important phenomena that has been observed in such systems, which is obtained by functionalizing plasmonic structures with excitonic materials, such as J- and H-aggregates,\textsuperscript{305-307} dye molecules,\textsuperscript{308} quantum dots (QDs),\textsuperscript{309-311} and TMDC monolayers.\textsuperscript{202-206,312} Given that the plexcitonic dynamics and Rabi oscillations possess a broad range of applications for next-generation nonlinear harmonic signal generation, low-threshold lasing, and quantum chemistry, thus, finding much stronger coupling and the generation of more pronounced Rabi splitting are in high demand. As a reliable method, the exquisite characteristics of toroidal metastructures have stimulated researchers to investigate plexciton dynamics in these platforms. In a recent study, by designing a NIR-resonant toroidal meta-atom (Figure 15a), Ahmadvand et al.\textsuperscript{313} demonstrated that adding PbS QD aggregates to the toroidal plasmonic metadevice supports strong plexcitonic coupling with the Rabi splitting of 150 meV. In Figure 15b, the SEM image of the fabricated meta-atom is displayed. Illuminating the structure with $\rho$-polarized incidence, the experimentally measured and numerically calculated transmission spectra (in vacuum) are obtained in Figure 15c, validating the excitation of a toroidal mode around 0.95 eV.

To study the spectral response of the metasystem in the presence of QDs, the authors utilized the sensitivity of the toroidal dipole mode to the coupling strength in the capacitive regions. In particular, to operate within the strong coupling regime, the coupling strength should exceed both emitter scattering and cavity loss rates,\textsuperscript{314,315} which can be handled using high $Q$-factor platforms. Besides, since the coupling strength is proportional to the inverse-square of the mode volume ($V^{-1/2}$), a small cavity is necessary to effectively confine the induced excitons from the organic molecules or 2D sheets.\textsuperscript{316} Figure 15d is a rendering for the developed metasurface in the presence of QDs. In this regime, to investigate the possibility of plexcitonic coupling, the Rabi splitting of toroidal dipole feature was examined both experimentally and numerically (Figure 15e). Here, the transmission amplitude in the absence and presence of QDs are quantitatively and qualitatively compared, indicating a prominent splitting of the toroidal dipole mode. It is important to note that the Rabi splitting of the induced mode is obtained using the following relation: $h \approx \left[ \left( \gamma_p - \gamma_e \right) / 2 \right]^{1/2}$,\textsuperscript{311,317} where $\gamma_p$ and $\gamma_e$ are the dissipation rates of the uncoupled plasmons and excitons, respectively, and $g$ is the coupling strength as: $g = \mu_n \left( 4\pi \hbar \cdot \cdot \cdot V \right)^{1/2}$, where $\mu_n = 17.5D$ is the transition dipole moment of QDs,\textsuperscript{319} $N$, $\lambda$, $c$, $e$, and $V$ are the number of excitons, wavelength of excitons, velocity of light in vacuum, dielectric permittivity, and mode volume, respectively. In that respect, the effective mode volume of the devised cavity can be written as $V = \left( \lambda / 10n \right)^3$.\textsuperscript{320} This led to robust Rabi oscillations and splitting of around $h\Omega$=150 meV. Next, employing the theoretical approach for QDs-mediated plasmonic metasystems under dipole-dipole interaction,\textsuperscript{321} energy variations and the associated detuning ($\Delta$) are plotted in Figure 15f. Based on the obtained dispersion profile, one can say that an anticrossing arc underpins $h\Omega$=150 meV splitting of the toroidal dipole mode.

Finally, as a fundamental parameter, the photoluminescence (PL) spectra was determined through calculating the probability of electron occupation in a given state using photonic density of states (PDOS) spectra. In theory, the emission decay rate is related to the PDOS of the photonic design, which means one can control the internal dynamics of a quantum object-mediated platform through the photonic media. Here, the toroidal unit cell creates an environment with a given $Q$-factor and a mode localized within a small volume that boosts the associated PDOS, leading to the following luminescence (plotted both numerically and experimentally in Figure 15g):\textsuperscript{322} $F_\rho = \frac{3}{4} \pi^2 \left( \lambda / n \right)^3 Q / V$, where $\lambda$ is the wavelength of the cavity with the material of refractive index of $n$, and $V$ is the volume of the excited mode.
10. Emerging Applications and Future Directions

Though the observation of toroidal multipoles in artificially engineered materials has been reported and analyzed in various types of photonic and plasmonic 3D metamaterials and quasi-infinite metasurfaces, the practical and commercial applications of such spectral features have yet to be demonstrated. As deliberated in this contribution, the important and recent advances in the use of artificial architectures with toroidal response to tailor efficient and high-responsive photodetectors, modulators, biosensors, nonlinear harmonic signal emitters, and waveguides were highlighted and presented. However, the intriguing features of this concept need to be exploited and extended to other fields of applied and real-world optical sciences. While novel approaches have been carried out to enhance the functionality and quality of toroidal features using metastructures, this optical framework still requires deep and comprehensive investigations. To address this demand, the use of all-dielectric toroidal meta-atoms has been considered as a prominent approach to develop low-loss and cost-effective next-generation photonic metadevices, which possesses their strong potential to control the light-matter interactions in various multiscale subwavelength photonic elements and instruments.

Substantial electromagnetic field localization, high sensitivity to the environmental perturbations, and high Q-factor lineshape are some of well-known characteristics of the toroidal dipole resonance that make the discussed resonant structures as promising platforms for developing advanced nanophotonics technologies. In addition, the ability to be excited using both 3D bulk and planar metastructures is a unique property of toroidal resonances that allows them to be employed in different concepts. As a fundamental member of the toroidal family, radiative toroidal dipole enables strong squeezing of fields in very small spots and efficiently interacts with the incident waves, which are important for developing resonant metastructure applications, such as low-threshold lasers, immunosensors, slow light, beam steering, and chiral medium. Last but not least, the strong field confinement ability of toroidal unit cells enables strong plexcitonic coupling and giant vacuum Rabi
oscillations across a wide range of spectrum extended from IR to THz band. Such toroidal dipole-inspired Rabi feature possesses a strong potential to be employed for various purposes, including quantum chemistry and nonlinear optics.

11. Conclusions

In this context, by presenting recently developed artificial toroidal platforms, we summarized the use of toroidal dipole spectral feature in modern and practical optics-based applications. It is demonstrated that how low-loss and weak far-field radiation characteristics of this mode were used towards boosting the responsivity and reliability of novel integrated devices for today’s nanophotonic and plasmonic circuits and systems. Our focused Review revealed the possibilities of exploiting the toroidal metaplatforms in designing number of applied devices including NIR light sensors, THz biosensors, DUV light nanosources, and high MD metamodulators. It is also shown that toroidal structures are able to support robust exciton-plasmon interactions and Rabi oscillations. We envisage that this Review will open new paths towards designing advanced photonic and plasmonic tools using toroidal excitations.

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Conflict of Interest

The authors declare no competing financial interest.

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Figures:
Scheme 1. Three families of dynamic multipoles. Artistic representation of charge configurations and far-field radiation patterns of electric, magnetic and toroidal multipoles.\(^{(67)}\) Copyright 2014, American Physical Society (APS).

Figure 1. Toroidal dipole-resonant 3D metamaterial. a) Representation of the 3D meta-atom, consisting of four split wire strips surrounded by a dielectric slab. b) and c) Magnetic moments of wire pixels during in-phase and out-of-phase interactions, resulted in the excitation of magnetic (I) and toroidal (II) dipole resonances, respectively. d) Close-up image of the fabricated metasystem. e) Toroidal metamaterial slab. f) Transmission and g) reflection spectra of the 3D metamolecule, showing the excitation of pronounced magnetic and toroidal dipole resonances. h) Multipole decomposition plot of the 3D unit cell. i) and j) Logarithmic magnetic field distribution lines for magnetic (I) and toroidal (II) dipole resonances, plotted on top of the color maps of magnetic energy density.\(^{(30)}\) Copyright 2010, Science (AAAS). Design and spectral response of toroidal dipole-
resonant 3D unit cell. k) Schematic of the devised meta-atom and formation of the toroidal dipole modes. l) and m) SEM images of the fabricated metamaterial in different scales. n) The simulated and (o) measured transmission spectra of the metamaterial for γ-polarized illumination. (p) Multipole decomposition plot of the meta-atom. (q) The simulated H-field (xy-plane) distributions at ω_1, ω_2, and ω_3. (r) Surface current distributions and magnetic dipole orientations on the plasmonic meta-atom at ω_1, ω_2, and ω_3. Copyright 2017, American Chemical Society (ACS).

Figure 2. Subwavelength 3D toroidal metamolecules. Artistic drawings, SEM image, and photographs of various metamaterials, based on 3D metallic and all-dielectric unit cells, considered for the excitation of dynamic toroidal dipole mode from IR to microwave frequencies. Figures reproduced with permission from: a) Ref. 32, ACS; b) Ref. 90, Wiley; c) Ref. 58, NPG; d) Ref. 72, John Wiley & Sons Inc.; e) Ref. 91, OSA; f) Ref. 92, AIP; g) Ref. 93, APS; h, i) Ref. 94, NPG.

Figure 3. Subwavelength planar toroidal metamolecules. Artistic drawings and SEM image of several metamaterials, based on planar metallic and all-dielectric unit cells, employed for the excitation of dynamic toroidal dipole mode from IR to microwave frequencies. Figures reproduced with permission from: a) Ref. 80,
Figure 4. All-dielectric toroidal dipole-resonant cluster. a) Schematic of the proposed all-dielectric metastructure. b) Normalized scattering cross-section with the dominant multipoles. c) and d) Transmission spectra of the devised platform in two different configurations. e) and f) Polarization currents (red arrows) and magnetic field (blue arrows) distributions, and the intensity maps of the magnetic and electric fields at $f_1^{(1)}$ and $f_2^{(2)}$, related to the intra-cluster (TD\textsubscript{intra}) and inter-cluster (TD\textsubscript{inter}) modes.\[105\] Copyright 2019, John Wiley & Sons Inc.
Figure 5. Toroidal plasmonic NIR-metasurface. a) Schematic representation and b) side-view picture of the plasmonic meta-atom. (c) FIB image of the circular V-groove array (scale bar: 2 μm). The inset presents 45°-downward front view (scale bar: 300 nm). d) and e) Calculated H-field distributions at $\lambda_1=639$ nm and $\lambda_2=716$ nm, respectively. f) Radiated power of different multipole moments. g) Numerical and experimental reflectivity at 30° incidence. Copyright 2014, Optical Society of America (OSA).
Figure 6. Toroidal plasmonic IR photodetector. a) Artistic drawing of the asymmetric toroidal meta-atom (not to scale). b) Experimental (solid line) and simulated (circles) transmission spectra, indicating the excitation of pronounced toroidal (2850 nm) and weak magnetic dipole (2150 nm) modes. SEM image of the fabricated sample arrays and the magnified version of it. c) Normalized absorption spectra of the toroidal unit cell for both substrate conditions. d) Numerically calculated and e) experimentally measured photogenerated currents at the Au/Ni electrodes for both substrates. f) Photoresponsivity ($\mathcal{R}$) and g) IQE of the toroidal photodetector for n- and p-type Si substrates. h) NEP and i) photodetectivity of the metadevice at 2850 nm. Copyright 2019, Royal Society of Chemistry (RSC).
Figure 7. Nonlinear plasmonic toroidal metadevice. a) Schematic of the prosoped metasurface. b) Top-view and c) cross-sectional drawings of the unit cell with geometric parameters. d) SEM image of the toroidal metasurface (scale bar: 400 nm). e) Experimental (solid) and numerical (dotted) transmission spectra. f) Plotted multipole decomposition. g) Charge distribution at resonance. h) Normalized and cross-sectional H-field distributions at the fundamental ($|H_{\text{pump}}(\lambda)|$) and THG ($|H_{\text{THG}}(\lambda)|$) wavelengths. i) Experimental and j) numerical third harmonic spectrum of the toroidal metasurface (red) and nanodimer array (green). k) Log-log power dependence of the THG of the toroidal metasurface (red) and nanodimer array (green). l) Intensity of the third harmonic signal versus ITO thickness for the toroidal metadevice (red) and nanodimer array (green).[81] Copyright 2019, American Chemical Society (ACS).
Figure 8. High-Q toroidal metasurface refractive index sensor. a) Artistic drawing and b) microscopic image of the toroidal metasurface. c) Meta-molecule of the toroidal platform coated with the analyte layer. d) Numerically calculated transmission spectra with and without the analyte layer. Simulated e) transmission spectra and f) correspondingly derived frequency shift versus refractive index plot, with an increasing refractive index. g) Simulated sensitivities for the analyte layer of different thicknesses, with Si and Mylar substrates. h) 4 µm-thick analyte layer coated metasurface with an increasing thickness of Si and Mylar substrates. Exponential fitting (dotted curve) is applied to obtain the maximum sensitivity value. Copyright 2017, American Institute of Physics (AIP). i) Schematic of the all-dielectric toroidal structure with the judiciously defined geometric parameters. j) Transmission spectra for different refractive indices. k) Toroidal resonant frequency shift as a function of k) refractive index and l) analyte thickness. Copyright 2019, Optical Society of America (OSA). THz toroidal metasurface integrated with a microfluidic channel. m) 3D view of the metadevice combined with a microfluidic channel. The inset panels are the top view and y-z cross-sectional view of the THz metasurface. n) Transmission spectra with refractive indices varied from $n=1.0$ to $n=1.8$. o) Frequency shift versus channel height when $n=1.6$. p) FoM variations as a function of the refractive index. Copyright 2019, Institute of Physics (IOP).
Figure 9. Toroidal plasmonic MIR biosensor. a) Artistic schematic of the toroidal unit cell in the presence of kanamycin sulfate molecules. b) SEM image of the fabricated metamaterial. c) Experimentally (orange) and numerically (blue) extracted transmission spectra under longitudinal (solid) and transverse (dashed) polarized beam. d) SEM image of an area of the metastructure in the presence of antibiotic molecules. e) Experimentally measured transmission spectra for different concentrations of antibiotic molecules. f) Toroidal dipole position as a function of the antibiotic molecules’ concentration. g) Experimentally obtained functional variations in the transmission before (dashed) and after (solid) binding conditions. Copyright 2019, American Physics Society (APS).

Figure 10. THz toroidal metaswitch. a) Microscopic image of the fabricated metasurface, under transverse polarized excitation. b) The magnified microscopic image of the Si paths mediated metamolecule with geometric parameters (in micrometers). c) An artistic demonstration of the formation of spinning toroidal dipole. d) Percentage modulation of the experimental transmission amplitude versus frequency for different pump fluences. e) Numerically calculated amplitude transmission spectra at different conductivities of Si pads. Copyright 2018, John Wiley & Sons Inc. NIR toroidal metaswitch. Normalized transmission spectra of f) the Fano resonant metastructure and g) toroidal metastructure. Here, the insets show the corresponding 3D
drawings. h) Schematic of the metallodielectric meta-atom with GST arcs. i) Transmission ratio of the GST-mediated unit cell for both GST states, a NIR plasmonic switch.\[226\] Copyright 2017, American Chemical Society (ACS).

Figure 11. Graphene-enhanced toroidal metamodulators. a) Schematic illustration of the THz metamolecule. b) Transmission spectrum of the metasurface without a graphene overlayer. c) The magnetic field distribution at resonance. The inset shows the magnetic field distribution on the y-z plane. d) Representation of the toroidal dipole excitation within the meta-atom. e) Numerical transmission spectra with and without the graphene overlayer. f) Corresponding E-field distributions for different Fermi energy levels of graphene.\[101\] Copyright 2017, Optical Society of America (OSA). g) Artistic drawing of the unit cell in the presence of graphene overlayer. h) Numerically calculated transmission spectra with and without the graphene layer. i) Associated distributions of the displacement current density |\(\mathbf{J}\)| for various Fermi energy levels.\[233\] Copyright 2017, Optical Society of America (OSA).
Figure 12. Toroidal photonic microwave waveguide. a) Schematic of an all-dielectric metasurface composed of cuboid arrays. b) Multipole decomposition with $w=8$ mm and $h=3.2$ mm. c) E-field profile at $f_{a}=10.57$ GHz. d) Power transmittance, reflectance, and losses spectra of the metasurface for $h=0.4w$, $w=8$ mm and $p=9.6$ mm. e) Multipole decomposition with $h=0.4w$. f) An artistic picture of f) an ideal parallel-plate waveguide (PPW) and g) a realistic parallel-plate waveguide. h) Power transmittance, reflectance, and loss spectra of both the ideal metasurface and realistic parallel-plate waveguide. i) Schematic of the microwave rectangular waveguide. j) Power transmittance, reflectance, and losses spectra of the waveguide. k) E-field profiles at 10.4 GHz and 8.9 GHz for different cuboids configurations. [270] Copyright 2019, Nature Publishing Group (NPG).
Figure 13. Toroidal-resonant polarization converter metasurface. a) Artistic layout of the metasurface and meta-atom with $w_1 = w_2 = 1400 \mu m$, $h_s = 20 \mu m$, and $h = 280 \mu m$. Simulated spectra of the transmitted b) power and c) phase of the all-dielectric metasystem. d) Schematic representation of the metasurface and phase shift mechanism, with the following geometries of Si disks: $h=280 \mu m$, $h_s=20 \mu m$, $w_1=1400 \mu m$, and $w_2=1350 \mu m$. e) Phase shift of $x$- and $y$-polarizations and difference between them. f) Transmitted optical power for $x$- and $y$-polarizations and relative phase shift. Copyright 2019, SPIE.
Figure 14. Kirigami metastructures for reconfigurable toroidal CD. a) Photographs of three different types of Kirigami metamaterials. b-d) Type-I, e-g) Type-II, h-j) Type-III Kirigami metamaterials. b, e, h) Measured transmission spectra of b, e, h) L-handed enantiomers and c, f, i) R-handed enantiomers. d, g, j) Measured CD spectra. [290] Copyright 2018, Nature Publishing Group.
Figure 15. Plexcitonic coupling in toroidal meta-atom. a) Artistic drawing of the proposed unit cell, including the geometric parameters. b) SEM image of the fabricated plasmonic meta-atom (scale bar: 100 nm). c) Measured and numerically obtained transmission versus photon energy without QDs. d) Schematic of the proposed toroidal metasurface in the presence of QDs. e) Measured and numerically calculated transmission in the presence and absence of QDs. f) Dispersion of plexciton as a function of detuning ($\Delta$). Grey arrow marked the Rabi splitting energy ($\sim$150 meV). The solid line is the fitting. g) Numerically and experimentally obtained PL. Copyright 2019, John Wiley & Sons Inc.

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This comprehensive review brings the physics behind the excitation of toroidal moments in artificially engineered subwavelength architectures and instrumentation of these platforms to light. The exquisite advantages and promise of toroidal resonances in both bulky and quasi-infinite metastructures underlie a plethora of modern practical applications in the field of plasmonics, photonics, optoelectronics, and nonlinear meta-optics.