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Efficient and broadband quarter-wave plates by gap-plasmon resonators

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Abstract: We demonstrate numerically that metal-insulator-metal (MIM) configurations in which the top metal layer consists of a periodic arrangement of nanobricks, thus facilitating gap-surface plasmon resonances, can be designed to function as efficient and broadband quarter-wave plates in reflection by a proper choice of geometrical parameters. Using gold as the metal, we demonstrate quarter-wave plate behavior at λ ≃ 800 nm with an operation bandwidth of 160 nm, conversion efficiency of 82%, and angle of linear polarization fixed throughout the entire bandwidth. This work also includes a detailed analytical and numerical study of the optical properties and underlying physics of structured MIM configurations.

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1. Introduction

The possibility to control the polarization state of light is of paramount importance in modern optics as many phenomena are polarization sensitive. For example, many spectroscopic and microscopy applications rely on the control and knowledge of polarization in order to extract as much information as possible from the sample under study. The general attempt, however, to miniaturize photonics to the nanoscale also leads to the demand of nanometer-sized wave
retarders, especially half- and quarter-wave plates that together enable the complete exploration of all polarization states.

Conventional wave retarders can be constructed from uniaxial (birefringent) crystalline materials, such as quartz, featuring two different refractive indexes, which results in a phase difference between components of the light with polarization along the two axes as the wave travels through the crystal [1]. By appropriately choosing the crystal thickness, it is possible to construct half- and quarter-wave plates. An alternative method to create birefringence, known as form birefringence, consists in periodically texturing on a subwavelength scale non-birefringent material, so that TE and TM waves experience different refractive indexes [2–5]. In relation to an effective medium approach, this is equivalent to designing anisotropic metamaterials. Whichever approach used, both types of birefringence usually only show moderate differences in the two refractive indexes of $\sim 0.1 - 0.2$ at optical wavelengths [1, 2], which amounts in quite bulky wave plates with thicknesses larger than the wavelength.

In the quest for ultrathin wave retarders, several approaches using plasmonic effects (i.e., metals) have been suggested. For example, a giant form birefringence of $\sim 2.7$ can be obtained in metallic nanoslit arrays at optical wavelengths [6], or the usage of a properly designed elliptical bull’s eye structure demonstrates extraordinary transmitted light with circular polarization [7]. Recent research on compact wave retarders at optical [8, 9], near-infrared [10–13], terahertz [14], and microwave wavelengths [15], however, is closely related to the concept of detuned electrical dipoles (DED) and metasurfaces. The latter can be viewed as a two-dimensional grating with a deep subwavelength thickness and a periodicity considerably smaller than the wavelength of interest so that diffraction can be ignored. The DED concept covers any plasmonic system that consists of two electric dipole resonances that are oppositely detuned from a central frequency, such as nanorods of different lengths [16, 17]. As the phase of the scattered light from a resonant structure changes by $180^\circ$ from the low to the high frequency side of the resonance, the two dipolar elements will scatter light with different phases (relative to the incident field) at the central frequency. This fundamental fact we have exploited in the design of a plasmonic quarter-wave plate in reflection by utilizing metasurface unit cells consisting of orthogonal dipolar scatters which for proper detuning ensure a phase difference of $\sim 90^\circ$ between TE and TM polarization near the design (central) frequency [18]. One may note the conceptual similarity to recent quarter-wave plate designs in transmission, where the metasurface unit cell is made of a thin metal film with two orthogonal slits of different lengths [9–12].

In this paper, we design at the free-space wavelength $\lambda \simeq 800$ nm an efficient (reflectance of $\simeq 82\%$) and broadband ($\simeq 160$ nm) quarter-wave plate in reflection based on a metal-insulator-metal (MIM) configuration in which the top metal layer is periodically structured according to the DED principle. Such MIM structures with nanometer-sized spacers are known to facilitate gap surface plasmon (GSP) resonances originating from efficient reflection of the GSP at the boundaries of the top layer structure [19–21]. The structured MIM configuration may also be viewed as a metasurface separated by a dielectric spacer to the metal back reflector [22]. This interpretation of the lower metal film/substrate as a reflector originates from the low frequency regime, where Ohmic losses are negligible and, consequently, all impinging light is reflected. In the visible and infrared regime, on the other hand, the periodically structured MIM configuration is in fact mainly used as efficient absorbers [23–28] or thermal emitters [29], which results from the GSP resonance and the associated strong field confinement in the spacer. In this work, however, we demonstrate that structured MIM configurations can remain reflective at the GSP resonance by a proper choice of spacer thickness and unit cell size; a result that paves the way for efficient wave plates in reflection. It should be mentioned that structured MIM configurations have previously been demonstrated to work as half-wave plates at visible wavelengths [8], although that work mainly focuses on the possibility of polarization conversion, leaving out any
considerations on how to achieve high reflection and a broadband response. Also, it has previously been demonstrated how the polarization of light can be efficiently manipulated in a transmission geometry consisting of layered metasurfaces [30]. That work, however, is limited to the microwave regime where Ohmic losses in metals are negligible.

This paper begins with a discussion of the effect of a metallic back reflector on the reflection coefficient of a metasurface and emphasizes important design considerations (Sec. 2). The metasurface is, for simplicity, considered to be made of prolate spheroids described by their point-dipole polarizabilities in the modified long-wavelength approximation (MLWA) [31]. Section 3 presents detailed full-wave calculations of the optical properties of structured MIM configurations for which the top metal layer consists of periodically arranged gold nanobricks [see Fig. 2(b)]. In Sec. 4, the figures of merit of the nanobrick MIM quarter-wave plate is presented and discussed. Conclusions are given in Sec. 5.

2. The effect of a back reflector on a metasurface: Design considerations

Before we discuss the optical properties of nanobrick MIM configurations, which are structures suited for fabrication with standard electron beam lithography, it is instructive to consider the analytically simpler problem of a metasurface of prolate metal spheroids described by their point-dipole polarizability \( \alpha_{ii} \) in close proximity to a metal back reflector. For notational simplicity and congruence with subsequent sections, the setup is termed a structured MIM configuration, though it does not possess GSP resonances which are characteristic of MIM structures.

Within MLWA, the polarizability of the prolate spheroids is defined as

\[
\alpha_{ii} = \frac{\alpha^0_{ii}}{1 - \frac{k^2}{\omega^2} \alpha^0_{ii} - \frac{k^2}{4\pi\varepsilon_0} \alpha^0_{ii}},
\]

(1)

where \( \alpha^0_{ii} \) are the diagonal elements of the electrostatic polarizability tensor (see, e.g., Ref. [32]), \( k \) is the wave number in the surrounding medium, and \( a_{ij} \) is the radius (major or minor axis) relevant for the given \( \alpha_{ii} \). The term proportional to \( k^3 \) arises from radiation damping, while the term proportional to \( k^2 \) takes into account the depolarization of the radiation due to the finite size of the spheroid.

In the following, we consider a three-layer medium for which the metasurface, which is optically thin, is placed at the boundary between medium 1 and 2 [see Fig. 1(a)]. Each bulk medium is characterized by the refractive index \( n_i \) and wave impedance \( Z_i \). Following the transmission-line approach [34], the metasurface is modeled as a homogeneous current sheet with the boundary conditions

\[
\hat{z} \times (E_1 - E_2) = 0, \quad \hat{z} \times (H_1 - H_2) = K_s,
\]

(2)

where \( E_i \) and \( H_i \) are the electric and magnetic fields in medium \( i \), respectively, \( \hat{z} \) is the unit vector in the z-direction, and \( K_s \) is the induced surface current equal to [time convention: \( \exp(-i\omega t) \)]

\[
K_s = -\frac{i\omega \alpha_{eff}}{\Lambda^2} (\hat{z} \times E_1).
\]

(3)

Here, \( \alpha_{eff} \) is the effective diagonal \( 2 \times 2 \) polarizability tensor taking into account the effect from all other spheroids and the inhomogeneity of the surrounding medium, and \( \Lambda \) is the unit cell period (assuming a square unit cell).

Without loss of generality, we assume the axes of the prolate spheroids to be oriented along the coordinate axes so that the \( 2 \times 2 \) reflection matrix \( \hat{r} \) only contains nonzero diagonal elements. Furthermore, we assume a normal incident plane wave propagating along the z-direction.
Fig. 1. (a) Sketch of a three-medium system with a metasurface positioned at the interface between medium 1 and 2. The incident plane wave propagates normal to the interfaces in the z-direction with polarization along the major axis of the prolate spheroids. The reflection coefficient in Eq. (4) corresponds to ‘r’ in the drawing. (b) Amplitude and (c) phase of the reflection coefficient for three different cases: (I) No metasurface and medium 3 is assumed to be gold [equivalent to \(Z_3 = Z_{Au}\) and \(\alpha_{ii} = 0\) in Eq. (4)], (II) Structured MIM configuration with medium 3 as gold [equivalent to \(Z_3 = Z_{Au}\) in Eq. (4)], (III) Metasurface in homogeneous surroundings [equivalent to \(Z_3 = Z_{Air}\) in Eq. (4)]. The other parameters are: medium 1 and 2 are assumed to be air, the prolate gold spheroids have major and minor axes 71 nm and 12 nm, respectively, the period is \(\Lambda = 230\) nm, thickness of medium 2 is \(t_s = 150\) nm, and the gold permittivity is described by interpolated experimental data [33].
It is evident from Fig. 1(b) that case (I) corresponds to simple reflection from a gold substrate, showing almost unity reflection for wavelengths above 600 nm. The phase of the reflection coefficient [Fig. 1(c)], however, displays a much stronger variation than what can be expected from the dispersion of gold. The additional phase shift arises from the term \( \exp(ik_0n_2ts) \), which accounts for phase retardation in the spacer layer, because we have chosen the reference plane at \( z = 0 \) in order to facilitate comparison with metasurfaces. Case (II) and (III) show, as expected, complementary behavior, where the MIM configuration demonstrates a strong dip in reflection at the resonance at \( \lambda \sim 800 \) nm; the property that makes such structures relevant as plasmonic absorbers. If we study the phase of the reflection coefficient, it is clear that both case (II) and (III) demonstrate a strong variation in the phase across the resonance interval due to the change in phase of the polarizability by 180°. Interestingly, though, the MIM configuration experiences a much stronger phase variation, showing a slope of \( \sim -3.7 \) degrees/nm at the resonance compared to \( \sim -1.2 \) degrees/nm for the isolated metasurface [case (III)], which owes to the additional phase manipulation possible with a dielectric spacer and metal back reflector. Consequently, the design of structured MIM wave plates with the DED concept requires, in general, a smaller detuning than the equivalent metasurface without back reflector. Moreover, the structured MIM configuration also allows the design of wave plates whose retardation is not limited to the 180°-change that can be achieved for metasurfaces without back reflector.

As a final comment, it should be noted that the analytical calculations presented in Fig. 1 agree well with full-wave simulations. Simulations also show that strong phase variation still exists at spacer thicknesses of \( ts \sim 50 \) nm. Summarizing, the above analytical example of a structured MIM configuration demonstrates the improved possibility to control the phase of the reflected light with, in general, a steeper slope at the resonance compared to an isolated metasurface. The example, however, also illustrates the main problem that reflection is low at the resonance. Accordingly, an efficient wave plate based on the structured MIM configuration must employ a scattering setup that minimizes the dip in reflection; an issue that is overcome in the following section.

### 3. The structured metal-insulator-metal configuration

It is well-known that two-dimensional metal strips (i.e., metal films of finite width) in a homogeneous dielectric environment possess retardation-based resonances whose resonance wavelengths scale (almost) linearly with the width of the strip [36]. If such a strip is supported by a thin dielectric spacer and a metal substrate [see Inset of Fig. 2(a)], a continuous-layer gap-plasmon resonator is created in which resonances are standing GSP waves that can be controlled by the width of the metal strip [20]. The term ‘continuous-layer’ refers to the fact that truncation is carried out only for the top layer of the MIM configuration. As shown in Fig. 2(a), such a configuration also displays an almost linear dependence of the resonance wavelength \( \lambda_{res} \) with respect to the width of the strip \( w \). The slope of the curve \( (d\lambda_{res}/dw) \) is influenced by the thickness of the spacer layer \( ts \), however, in any case it is easy to control the resonance wavelength in the visible and near-infrared regime.

Based on the excellent resonance characteristics of continuous-layer GSP resonators, we have chosen to employ the three-dimensional analog structure as the unit cell of our structured MIM wave plate [Fig. 2(b)]. The structured top metal layer consists of gold nanobricks with lengths \( L_x \) and \( L_y \), and height \( t \) which are separated by a distance \( ts \) to the gold substrate. The spacer medium is assumed to be SiO\(_2\) with refractive index \( n_s = 1.45 \), while the upper medium is taken to be air. One should note that by selecting \( L_x \neq L_y \) we obtain a structure with two detuned orthogonal GSP resonances. We have chosen the lower metal part to be of infinite extend for simplicity, though it should be emphasized that a gold film of \( \sim 50 \) nm thickness would produce almost similar results, thus keeping the overall thickness of the wave plate...
Fig. 2. (a) Resonance wavelength $\lambda_{res}$ as a function of the strip width $w$ for the continuous-layer GSP resonator depicted in the inset. In the calculations, the metal strip and substrate are assumed to be gold and the spacer is SiO$_2$ with refractive index $n_s = 1.45$. The height of the strip is $h = 50$ nm. (b) Sketch of the structured MIM unit cell used in the design of a quarter-wave plate in reflection. The metal parts are assumed to be gold, the spacer is SiO$_2$, and the upper dielectric is air. In this work, the nanobrick dimensions are fixed at $t = 50$ nm, $L_x = 138$ nm, $L_y = 105$ nm, and the corners are rounded with a radius of 5 nm.

Fig. 3. Reflection as a function of wavelength and unit cell period for the nanobrick MIM configuration in Fig. 2(b). The nanobrick parameters are $t = 50$ nm, $L_x = 138$ nm, $L_y = 105$ nm, and the incident wave is normal to the surface and x-polarized. Green dashed curve, excitation wavelength of (1,0) SPP; Blue dashed-dotted curve, excitation wavelength of (1,1) SPP; magenta dotted curve, resonance wavelength of GSP mode for isolated structure ($\Lambda \to \infty$). (a) $t_s = 20$ nm, (b) $t_s = 50$ nm.

subwavelength. The unit cell is chosen to be square with period $\Lambda$.

Fixing the dimensions of the nanobrick to $t = 50$ nm, $L_x = 138$ nm, $L_y = 105$ nm in this work, Fig. 3 shows reflection maps for normal incident and x-polarized light. The calculations are performed using the commercial finite element software Comsol Multiphysics by applying periodic boundary conditions on the side walls of the unit cell and perfectly matched layers (PML) at the truncation boundary in the upper air region. It is evident from Fig. 3 that three distinct modes give rise to reflection dips, where the exact location of the dips depends on the unit cell period. In agreement with a previous work [37], two of the modes correspond to excitation of propagating surface plasmon polaritons (SPPs) by grating coupling, whereas the third mode is the localized GSP resonance. Grating coupling arises for normal incident light.
The nontrivial parameters are \( t_z = 50 \text{ nm} \) and \( \Lambda = 700 \text{ nm} \).

when \( \Lambda = \lambda_{\text{spp}} \sqrt{p^2 + q^2} \), where \( \lambda_{\text{spp}} \) is the wavelength of the SPP, and \( p \) and \( q \) are integers. Figure 3 displays with dashed and dashed-dotted lines the coupling to \((p,q) = (1,0)\) and \((1,1)\) SPP modes, respectively, calculated by neglecting the presence of the nanobrick array. Despite this approximation, good correspondence is found between SPP excitation wavelengths and dips in reflection spectra. A large part of the discrepancy can actually be attributed to the anti-crossing behavior occurring when SPP and GSP modes begin to strongly couple.

The origin of the reflection dips can also be verified by a simple inspection of the mode profile at the three different reflection dips. As an example, Fig. 4 displays the H-field of the three modes for \( \Lambda = 700 \text{ nm} \) in the \( xz\)-plane (\( y = 0 \)) and in the \( xy\)-plane in the center of the spacer layer. The GSP mode shows strong H-field enhancement in the spacer [Fig. 4(a)], which is characteristic of the fundamental GSP mode due to the anti-symmetric current distribution in the two metal parts. Furthermore, the strong localization of the H-field to the region below the nanobrick [Fig. 4(d)] confirms the localized nature of the mode. It is worth noting that the fundamental GSP mode possesses an electrically driven magnetic response [38], which is why the mode is known as the magnetic resonance in the metamaterial community [39, 40]. Additionally, the fundamental GSP mode is conceptually similar to resonances associated with high-impedance surfaces at microwave frequencies [41, 42]. The two SPP modes do not show the same degree of enhancement and localization. For example, both SPP modes demonstrate a H-field on top of the nanobrick that is comparable or higher than the field in the spacer [Figs. 4(b) and 4(c)], which is a signature of an extended mode. Furthermore, the fields in the spacer layer represent interference patterns; Fig. 4(e) corresponds to interference of two waves with...
wave vectors $k_x = \pm 2\pi/\Lambda$ [in Fig. 4(e) the nanobrick perturbs the field below it], which fits in with the $(1,0)$ SPP mode, whereas Fig. 4(f) results from interference of four waves with wave vectors $(k_x, k_y) = (\pm 1, \pm 1)2\pi/\Lambda$, i.e., the $(1,1)$ SPP mode.

Retuning to Fig. 3, it is clear that the reflection depends strongly on the period as well as on the thickness of the spacer layer. In relation to the latter parameter, the GSP mode shows an increased confinement of the field in the spacer for decreasing spacer thickness, which results in a stronger reflection dip as less light is scattered to the far-field (i.e., the GSP is efficiently reflected from the nanobrick boundaries). The situation is different for the SPP modes, because the SPPs become less confined to the metal-dielectric interface for decreasing $t_s$, thereby resulting in reduced propagation losses and less pronounced dips in the reflection spectra. In relation to the effect of the unit cell period, the excitation of SPP modes are by the grating coupling directly dictated by $\Lambda$. Consequently, SPP modes do not exist for subwavelength periods. The GSP mode exists, on the other hand, for any unit cell period, however, the mode is still influenced by $\Lambda$. This is especially apparent for small periods where the mode starts to red shift and broaden with a simultaneous decrease in the reflection dip. The behavior is ascribed to the near-field interaction with neighboring nanobricks, thus modifying the optical properties of the isolated nanobrick MIM configuration.

In the design of a quarter-wave plate in reflection, several conclusions can be drawn from Fig. 3. The demand of a subwavelength period to facilitate a metasurface is in fine line with the request to avoid SPP modes at the design wavelength in order not to complicate things unnecessarily. Furthermore, subwavelength periods weaken the reflection dip of the GSP mode, which makes it possible to design efficient wave plates. At first, one might think that the broadening of the GSP mode at subwavelength periods may lead to nanobrick designs with relatively large $L_x/L_y$-ratio (i.e., detuning) in order to create a $90^\circ$ phase difference between the two orthogonal GSP resonances. The dramatic change in reflection phase at resonance for structured MIM configurations [see Fig. 1(c)], however, ensures a modest $L_x/L_y$-ratio of $\sim 1.3$ for the quarter-wave plate design (Sec. 4). Finally, the spacer thickness $t_s$ should be chosen sufficiently large so as to ensure sufficiently strong near-field interactions (leading to high reflectivity) due to GSP mode extending beyond the nanobrick [20] at reasonably large lattice constants that are desirable from the fabrication viewpoint.

4. Quarter-wave plate in reflection

In the preceding sections, we have discussed the effect of a metal back reflector on the reflection coefficient of a metasurface, and we have thoroughly studied the optical properties of the nanobrick MIM configuration, emphasizing parameter regions for which an efficient quarter-wave plate in reflection can be constructed. In this section, we demonstrate a wave plate design at the wavelength $\lambda \simeq 800$ nm using the nanobrick dimensions of Sec. 3 with the spacer thickness $t_s = 50$ nm and period $\Lambda = 240$ nm. The corresponding reflection coefficients for normal incident x- and y-polarized waves are shown in Fig. 5(a). It is seen that for both polarizations the reflection coefficient remains high at $|r_\parallel| \sim 0.9$ for $\lambda > 700$ nm without any pronounced feature of the GSP resonances. Despite this fact, it is evident that the phase difference between the two complex reflection coefficients $\Delta \Phi$ experiences a maximum equal to $\sim 90^\circ$ at $\lambda = 800$ nm, i.e., the configuration shows quarter-wave plate operation.

Following the discussion in Ref. [9], the bandwidth of operation can appropriately be defined by $\pm 10^\circ$ change in $\Delta \Phi$, which results in a bandwidth of 160 nm corresponding to the wavelength interval 720-880 nm, [see Fig. 5(a)]. The bandwidth is also depicted in Figs. 5(b) and 5(c) by the cyan-colored areas. Although not pursued in this work, it is worth noting that the bandwidth can be further increased by deliberately designing the quarter-wave plate to show $\Delta \Phi = 100^\circ$ at the design wavelength.
Fig. 5. (a) Reflection coefficients for normal incident $x$- and $y$-polarized light for the nanobrick MIM configuration in Fig. 2(b) with $t_s = 50$ nm and $\Lambda = 240$ nm. Here, $\Delta \Phi = \arg(r_{xx}/r_{yy})$. (b) Reflectance and absorption for normal incident circularly-polarized light. The cyan-shaded area depicts the operation bandwidth. (c) Degree and angle of linear polarization (DoLP and AoLP, respectively) for normal incident left and right circularly polarized light (LCP and RCP, respectively). AoLP is measured from the x-axis.

Figure 5(b) depicts the reflectance and absorption for circularly polarized incident light (the configuration is insensitive to the handedness of the light as it does not possess optical activity), and it is seen that the reflectance is only weakly increasing in the operation bandwidth with an average reflectance of $\approx 82\%$. This value achieved for a realistic metal with losses included is due to the presence of the metal back reflector, and it is a considerable improvement compared to $\sim 50\%$ theoretically predicted for a single lossless isolated metasurface [9]. The reflectance is expected to increase even further with the use of silver instead of gold.

An alternative way to describe the figure of merit of the quarter-wave plate is through the degree of linear polarization (DoLP) defined by the Stokes parameters $\text{DoLP} = \frac{s_1^2 + s_2^2}{s_0}$, where $s_0 = |E_x|^2 + |E_y|^2$, $s_1 = |E_x|^2 - |E_y|^2$, and $s_2 = E_x^*(E_y) + E_y^*(E_x)$ [32]. Here, ‘*’ means complex conjugate and the superscript ‘r’ refers to the reflected electric field. The DoLP of the reflected light is displayed in Fig. 5(c) for circularly polarized incident light, showing a value close to unity in the entire operation bandwidth (DoLP $> 0.96$), which is equivalent to reflected light with linear polarization. Another important parameter is the angle of linear polarization (AoLP), which describes the polarization angle of the linearly reflected light with respect to the x-axis for incident light with circular polarization. From Fig. 5(c) it is seen that the angle of polarization is almost constant at $\pm 45^\circ$, where the sign depends on the handedness of the incident wave (the variation in AoLP is less than $2^\circ$ within the bandwidth). This insensitivity of AoLP to the wavelength is a direct manifestation of the weak dispersion in the amplitude of
the reflection coefficients [see Fig. 5(a)]. From a practical point of view, the weak wavelength dependence in AoLP is a desirable property, as it is equivalent to fixed fast and slow axes of a conventional quarter-wave plate.

5. Conclusion

In conclusion, we have numerically considered realizable MIM configurations in which the top metal layer consists of a periodic arrangement of nanobricks. Although such structures typically are used as efficient absorbers due to the properties of GSP resonances, we demonstrate that by choosing a subwavelength period and avoid strong coupling between the nanobricks and the metal substrate it is possible to keep the structure reflective at the GSP resonance. Accordingly, efficient quarter-wave plates in reflection can be designed by a proper ratio between the sides of the nanobrick, which ensures a phase difference of 90° for polarization along the two main axes. As an example, we demonstrate quarter-wave plate behavior at $\lambda \simeq 800$ nm with an operation bandwidth of 160 nm. Despite using gold as the metal, the configuration converts 82% of the incoming light with an angle of linear polarization fixed throughout the entire bandwidth. By replacing the metal substrate by a thin metal film ($\sim 50$ nm), we believe that an attractive subwavelength-thin polarization converter in reflection can be constructed and implemented in nanoscale photonic circuits.

Finally, we believe that the presented detailed analytical and numerical discussion of the optical properties and underlying physics of structured MIM configurations are not only helpful in the design of plasmonic wave plates, but also include important considerations in relation to plasmonic super absorbers and thermal emitters.

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