Reflectarray Design at Infrared Frequencies: Effects and Models of Material Loss

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***Abstract*—Reflectarray designs at infrared (IR) frequencies are investigated in this paper. At the short-wavelength region, material loss becomes an important consideration in reflectarray designs. Based on the measured properties of conductors and dielectrics at infrared frequency, this paper investigates the loss effects on the reflection magnitude and phase of reflectarray elements. It is revealed that when the material loss exceeds a certain limit, the element reflection phase will vary within a narrow phase range instead of a full 360° phase range. An equivalent circuit model is used to understand this phenomenon. Based on the investigation, alternative design methods for infrared reflectarrays are suggested to lower the loss effect. The low loss reflectarrays have great potential for infrared and visible range applications, such as a low profile planar concentrator for solar energy systems.**

***Index Terms*—Infrared, loss effects, nanotechnology, reflectarray, solar power.**

I. INTRODUCTION

ELECTROMAGNETIC waves cover a wide frequency spectrum, including microwaves and optics. The wave behavior at both microwave and optical frequencies follows Maxwell's equations; hence many microwave concepts have been extended to optics, and in turn a lot of optical designs have been translated to microwave frequencies. For example, the invention of optical fiber [1], a kind of dielectric waveguide, has greatly propelled the development of optical communications and the Internet. In addition, resonant optical antennas [2], are recently being studied that could contribute to the improvement of light emitters in the future [3]–[5]. In this paper, the reflectarray, an advanced microwave antenna concept, is explored at infrared frequency. This concept may be extended to potential applications in concentrating solar power (CSP) systems.

A reflectarray antenna combines the advantages of both printed arrays and reflector antennas, and has low-profile, low mass, and low cost features [6]–[8]. The reflectarray has received considerable attention over the years and is quickly finding many applications [9]–[11]. Reflectarray antenna designs at terahertz and optical frequencies however, are a rather new and challenging study [12], [13]. To design a reflectarray operating at infrared frequency with a 10 μm wavelength, the size of reflectarray element is around 5 μm (half wavelength) and the substrate thickness is in the order of 0.1 μm. Thus, a practical barrier for infrared reflectarray design was the limited fabrication capability at a competitive cost. In recent years, nanotechnology has emerged as a revolutionary technological breakthrough, which has led to the creation of many new materials and devices with a wide range of applications in medicine, electronics, and energy production. Thanks to the latest progress in nano fabrication techniques, the fabrication accuracy has been significantly improved at an affordable cost [14]. Therefore, it is possible now to design a reflectarray antenna with nanometer accuracy for infrared applications.

A high gain reflectarray is the same in principle as a sunlight collector in a CSP system, because they both focus the electromagnetic energy within a narrow beam. Compared to conventional solar panels, the CSP system has a significant cost advantage since the solar collector is less expensive than an equivalent area of solar cells. In addition, low-profile and planar reflectarrays are easy to fabricate and integrate, and the individually controlled element phase increases the focusing flexibility and enhances the system capability. For example, the reflectarrays can focus the solar energy onto a specified area with high concentration and uniform distribution instead of focusing all energy at a specific point. This feature is desirable in a CSP system, because it avoids over-illumination at a specific point and provides high efficiency over the entire solar cell surfaces. On the other hand, several challenges and technological limitations exist here which need to be resolved. For a practical system design, efficiency, bandwidth, and fabrication capabilities are of major concerns and must be investigated. While several methods to improve the efficiency and bandwidth of reflectarrays are available in the literature [6], currently a major concern for optical designs is the fabrication limitations. However with the rapid advancement of nano fabrication, it is believed that the concept

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of reflectarray antenna could be extended to optical frequencies in the near future.

This paper presents our initiative work on reflectarray designs at infrared frequency. Material loss is always a concern in reflectarray designs [7], [15]. At microwave frequency, since a high conductivity is obtained for conductors and a low loss tangent can be achieved for substrates, the gain loss of a reflectarray due to the materials is relatively small. At optical frequency, the losses in substrates and conductors are severe, and their effects on reflectarray element designs become a critical issue. In this paper, the loss effects on the magnitude and phase of the reflection coefficient are investigated, and an equivalent circuit model is used to understand the loss behaviors. Based on the study, some alternative design methods for infrared reflectarray elements are suggested.

II. OPTICAL PROPERTIES OF MATERIALS

A. *Optical Measurements and EM Parameters*

Optical properties of materials were measured using a Woollam variable angle spectroscopic ellipsometer (IR-VASE) [16]. From these measurements the complex index of refraction of materials are determined across the frequency band of interest. Electromagnetic simulations however require material property definitions as complex dielectric constants. Therefore, the measured data from the ellipsometer needs to be converted using

$$\tilde{\varepsilon}_r(\lambda) = \tilde{n}^2(\lambda) \tag{1}$$

where $\tilde{n} = n + jk$ is the complex index of refraction. For dielectric materials the dielectric constant and loss tangent are calculated as

$$\varepsilon_c = \varepsilon_0(\varepsilon_r' + j\varepsilon_r'') = \varepsilon_0(n^2 - k^2 + j2n\,k), \tag{2a}$$

$$\tan\delta_e = \frac{\varepsilon_r''}{\varepsilon_r'} = \frac{2nk}{n^2 - k^2}. \tag{2b}$$

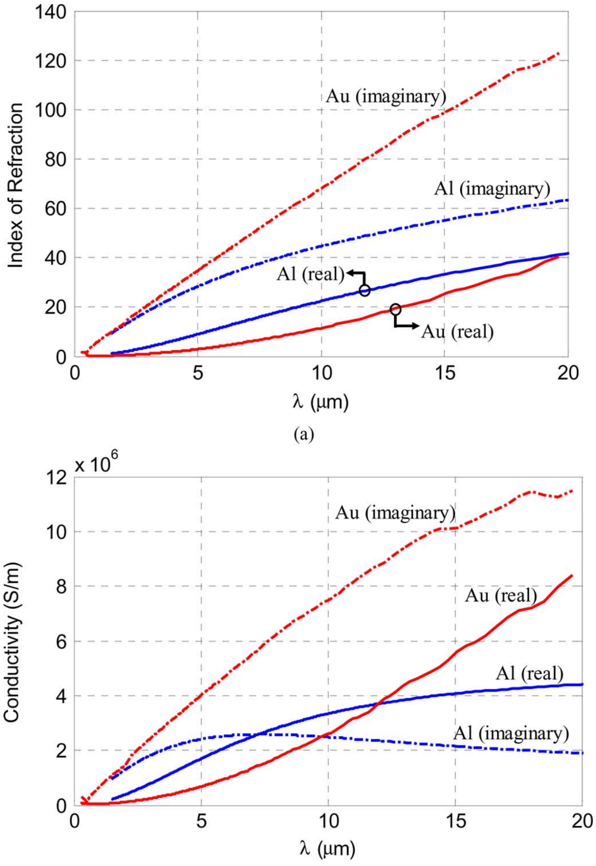
In these equations, the $e^{-j\omega t}$ time convention is assumed. For conductors the electromagnetic property of interest is the conductivity which is related to the index of refraction as

$$\sigma = j\omega\varepsilon_o(1 - \tilde{n}^2) = \omega\varepsilon_o[2nk + j(1 - n^2 + k^2)]. \tag{3}$$

These optical properties of material can now be directly implemented in electromagnetic (EM) simulators. It should be pointed out that as with any measurement data, the IR-VASE is susceptible to measurement and post processing errors, however by detailed analysis of the standard deviation of the measured response and material model errors, the measured optical properties should be within ±5% of their actual values [17].

B. *Measured Results*

Fig. 1 shows the material properties of some conductors used at infrared frequencies. To reduce metallic losses, gold is typically used as conductors at high frequencies; however it can be seen that the conductivity of gold at infrared is in the order of one tenth of its nominal value.



(a)

(b)

Fig. 1. Measured material properties of various conductors at infrared: (a) index of refraction, (b) conductivity.

Fig. 2 shows the material properties of two dielectric materials: benzo-cyclo-butene (BCB) and silicon (Si). Here BCB is a spin-on polymer (Dow Cyclotene). Although Si shows a superior low loss performance, in comparison BCB tends to be a better candidate for the reflectarray substrate due to its lower dielectric constant [12], [13], [18], [19].

III. LOSSES IN REFLECTARRAY UNIT-CELLS

The aim of the study is to understand the loss mechanism in the unit-cells, therefore to simplify the problem the effects of the conductor loss in the metal patch and dielectric loss in the substrate are investigated separately, and the ground plane is assumed to be a perfect electric conductor (PEC). The element studied in this section is a 3×3 μm square patch in a unit-cell with periodicity of 5.54 μm. The dielectric substrate $(\varepsilon_r = 2.2)$ has a thickness of 450 nm. The simulations were carried out using commercial electromagnetic softwares Ansoft Designer [20], Ansys HFSS [21], and CST MWS [22]. A good agreement between the results was observed, hence only the results obtained by Ansys HFSS are reported here for brevity. It should be noted here that the reflection characteristics of the elements are obtained under normal incidence excitation, which is a reasonable approximation for oblique angles less than 30° [23].

To study the conductivity effect, we consider a lossless dielectric and investigate the reflection characteristics of the unit-

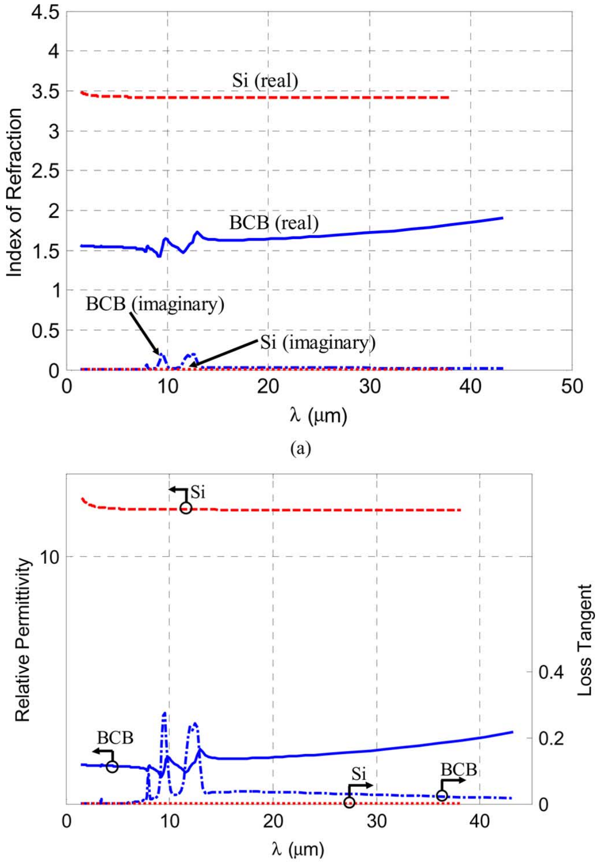


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Fig. 2. Measured material properties of various dielectrics at infrared: (a) index of refraction. (b) relative permittivity and loss tangent.

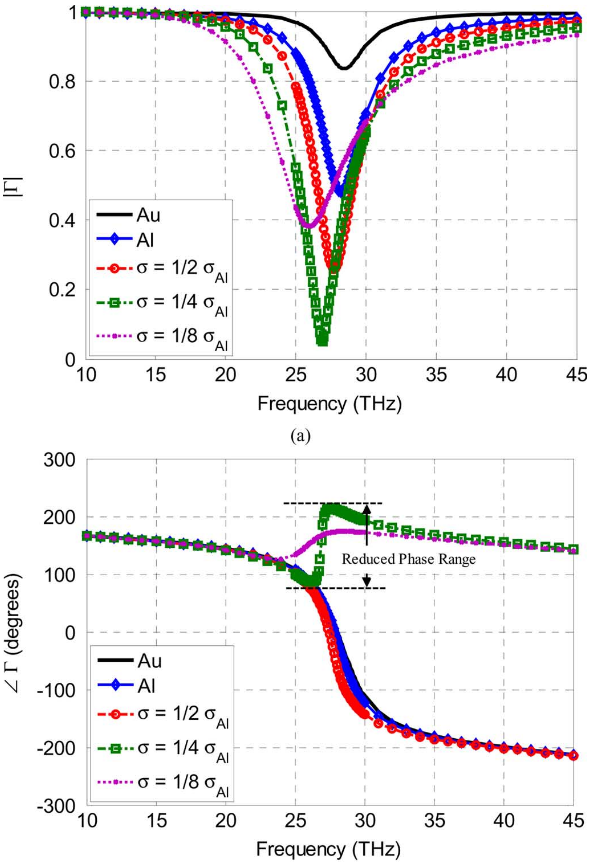

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Fig. 3. Simulated effect of conductor losses on the reflection coefficients of IR unit-cells: (a) reflection magnitude. (b) reflection phase.

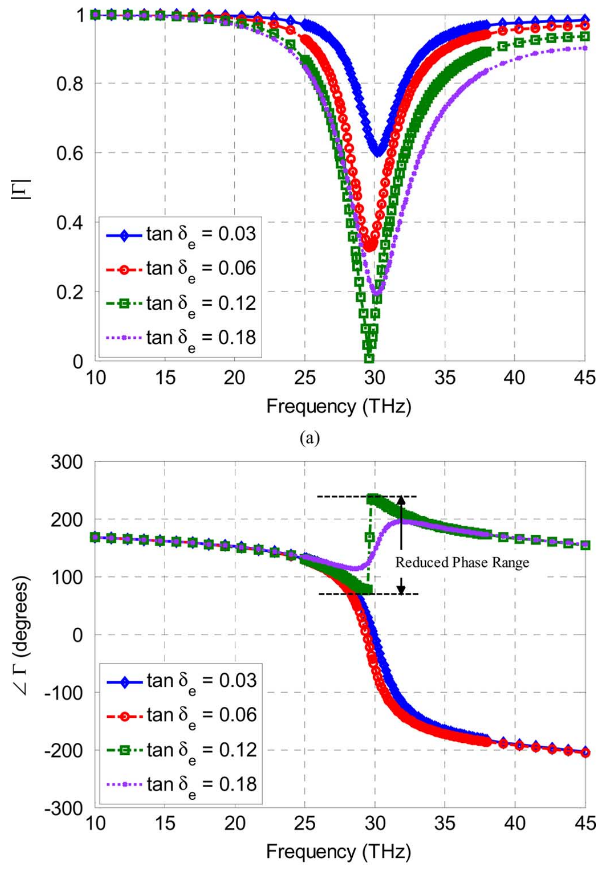
cells using different conductors for the patch. It is important to point out that when modeling conductors at THz and optical frequencies a zero thickness approximation is inaccurate for practical designs. Furthermore, the conductivity has to be modeled as a complex number, unlike microwave frequencies where typically only the real value of conductivity is used for simulations. In our studies the patch has a thickness of 100 nm and the conductors are simulated with the Drude models that are obtained from the measured data in Fig. 1. Fig. 3 shows the reflection characteristics of these elements.

From these results it can be seen that while the performance of a gold patch is quite acceptable in this frequency range, when an aluminum patch is used for the phasing element, less than half of the incident field will be reflected back from the elements. To study the effects of lower values of conductivity, we use the Drude models with values proportional to the aluminum case. It can be seen that as the metal conductivity decreases, the losses will increase. When the conductivity is reduced to one quarter of the value of conductivity for aluminum, almost a total loss of power will be observed. The phase response of this case is completely different from the typical S-curve. Instead of a 360° phase range, a reduced range of 150° is observed. When the conductivity is further reduced, it is interesting to observe that reflection magnitude increases, indicating a decreasing energy loss. However, the phase range becomes even smaller with this conductivity.

To study the effect of dielectric losses in the unit-cell we consider the case of a PEC patch on dielectric substrates with various loss tangents. For this study we have assumed that the dielectric properties are constant over the frequency band. It is implicit that in practical designs the dispersive nature of the parameters must be taken into account for accurate calculation of the reflection coefficients.

Fig. 4 shows the reflection characteristics of these elements. It can be seen that with increase of the dielectric losses, the losses in the element increases and for $\tan\delta_e = 0.12$ almost total loss is observed at the resonance frequency. When the dielectric losses are increased beyond this critical limit the losses in the unit-cell decrease; however, the reflection phase does not return back to the typical S-curve.

In summary, there exist two lossy situations in the reflectarray unit-cell designs. When the metal conductivity is above a certain limit or the dielectric loss tangent is below a certain value, the phase of reflection coefficient varies with a 360° range. In this situation when the conductor and dielectric losses increase but do not exceed the limit, the element loss will increase, however it will not affect the phase range. On the other hand when the metal conductivity is decreased or the dielectric loss tangent is increased beyond the limits, a new phase curve is observed with a limited angular range. In this situation when metal conductivity decreases or the dielectric loss tangent increases, the phase range becomes even smaller. The traditional reflectarray



(a)

(b)

Fig. 4. Simulated effect of dielectric losses on the reflection coefficients of IR unit-cells: (a) reflection magnitude. (b) reflection phase.

design at microwave frequency has the loss situation in the first category. The reflectarray design at infrared may have both loss situations because of the high loss material properties.

It should be noted that for a practical reflectarray design, a variable size patch is typically used for the phasing elements. Simulations were performed to quantify the effect of changing the patch dimensions at a constant frequency. Although the results are not reported here, a similar trend was observed for these designs, i.e., as the losses increased beyond a certain limit, the shape of the reflection phase versus patch size changed and the phase range reduced.

IV. Circuit Model Analysis and Discussions

A. Circuit Theory

The unit-cell structure can be modeled as a transmission line circuit as shown in Fig. 5. In each unit-cell the square metallic patches act as parallel capacitors with the adjacent cells while the short circuited unit-cell ground can be modeled as a parallel inductor. This circuit model has previously been implemented for lossless reactive impedance substrates [24]. The loss in the dielectric substrate can be modeled by a parallel resistor, i.e., the total unit-cell is modeled as a parallel *RLC* circuit. To model the conductor loss in the patch, a resistor will be series connected to the capacitor as shown in [25]. It should be noted here that if complex conductivity of the metal is to be taken into account, additional capacitors or inductors have to be included with the resistor, whose values would depend on the particular material. In this section we use the parallel *RLC* circuit model to understand the loss behavior in Fig. 4. Similar derivations can be obtained for conductor loss analysis.

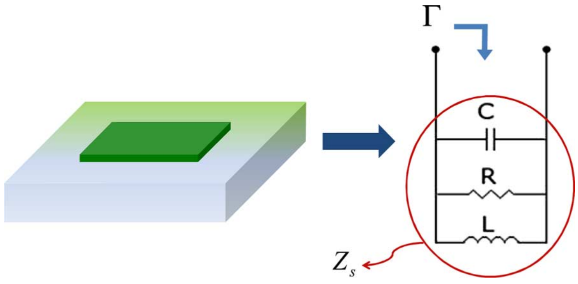


Fig. 5. Circuit model for the unit-cells.

Using this parallel *RLC* model the impedance of the surface $(\mathrm{Z_s})$ can be calculated directly. The reflection coefficient Γ of an incident plane wave on the unit-cell can then be calculated using transmission line theory, i.e.,

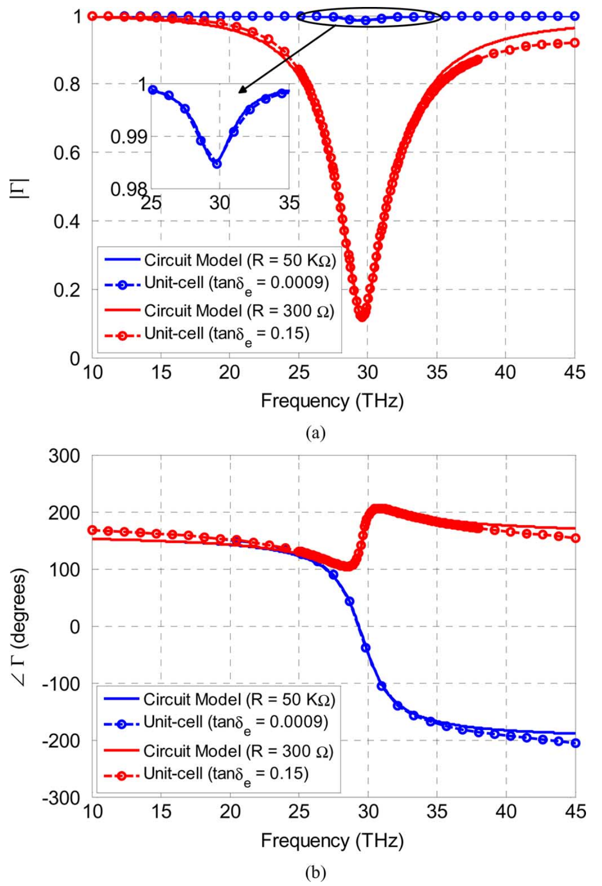
$$\Gamma = \frac{Z_s - Z_o}{Z_s + Z_o} \tag{4}$$

where $\mathrm{Z_o}$ is the free space impedance. The reflection coefficient in the S-plane is calculated as

$$\Gamma(S) = -\frac{S^2 + S\left(-\frac{1}{Z_oC} + \frac{1}{RC}\right) + \frac{1}{LC}}{S^2 + S\left(\frac{1}{Z_oC} + \frac{1}{RC}\right) + \frac{1}{LC}}. \tag{5}$$

Using this model the reflection properties of a lossy unit-cell can be calculated directly.

Let's consider two cases, the low loss $(\tan\delta_\mathrm{e} = 0.0009)$ and high loss $(\tan\delta_\mathrm{e} = 0.15)$ dielectric substrates. The values of the lumped elements in the circuit model are obtained by initially designing an *RLC* circuit resonating at 28.3 THz and then tuning these values so that the circuit model reflection curve fits the curve obtained by the full wave unit-cell simulations. The comparison of full wave simulation and circuit model are shown in Fig. 6. It can be seen that the circuit model shows good agreement with the full wave simulations in both cases where the values used for the capacitor and inductor are 0.134 fF and 0.215 pH, respectively. It should be pointed out that these lumped element values are for the case of normal incidence on the unit-cell, however a similar derivation can be obtained for the oblique incidence case. Comparing the resistor values in the circuit model, it can be seen that in the low loss case the parallel resistor is significantly large, so there is less power dissipated in the resistor. For the high loss case however the resistance comes close to the free space impedance, and as a result of the high power transfer to the resistor, almost no power is reflected back from the system near the resonant frequency. As expected the reflection phase of the circuit model also shows that this high loss will considerably change the reflection phase behavior of the unit-cell.



(a)

(b)

Fig. 6. Comparison between circuit-model and unit-cell simulations for low loss and high loss cases: (a) reflection magnitude, (b) reflection phase.

B. Zero-Pole Analysis of Element Performance

In the previous sections it was shown that when the losses in the unit-cell material increase beyond a certain limit, the typical S-curve of the reflection phase which shows a phase range of about 360° is no longer observed. The high losses change the traditional S-shape phase curve and create a new phase curve which has a narrow phase range. The unit-cell circuit model provides a helpful tool to obtain an insight into this unusual behavior. Three different cases are considered for the value of the resistor, $\mathrm{R} \to \infty, \mathrm{R} = \mathrm{Z}_0$ and $\mathrm{R} < \mathrm{Z}_0$. In the first case i.e., the lossless model, the reflection coefficient can be simplified to

$$\Gamma(S) = -\frac{S^2 - S\frac{1}{Z_oC} + \frac{1}{LC}}{S^2 + S\frac{1}{Z_oC} + \frac{1}{LC}}. \tag{6}$$

The function has two poles located on the left side of the S-plane and two zeros on the right side of the S-plane. As the frequency goes from $\omega = 0$ to $\omega \to \infty$, the total phase changes from 180° to $-180°$, indicating a complete phase range and total reflection $|\Gamma(\mathrm{S})| = 1$. The phases of numerator and denominator in (6) and the total phase are plotted in Fig. 7.

When $\mathrm{R} = \mathrm{Z}_\mathrm{o}$ the reflection coefficient will be

$$\Gamma(S) = -\frac{S^2 + \frac{1}{LC}}{S^2 + S\left(\frac{2}{Z_oC}\right) + \frac{1}{\mathrm{LC}}}. \tag{7}$$

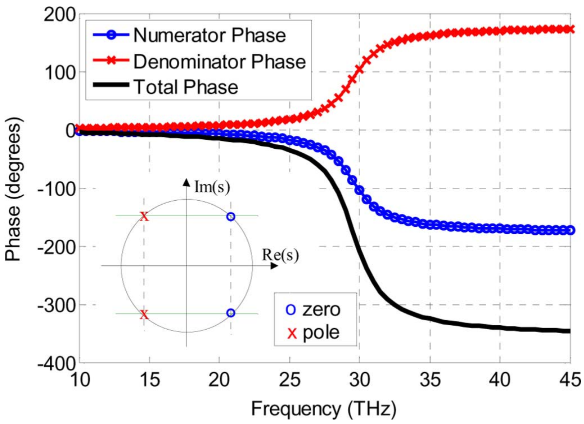


Fig. 7. Reflection coefficient analysis for the lossless case $(\mathrm{R} \to \infty)$. The positions of poles and zeros in the S-plane, and the corresponding phase versus frequency.

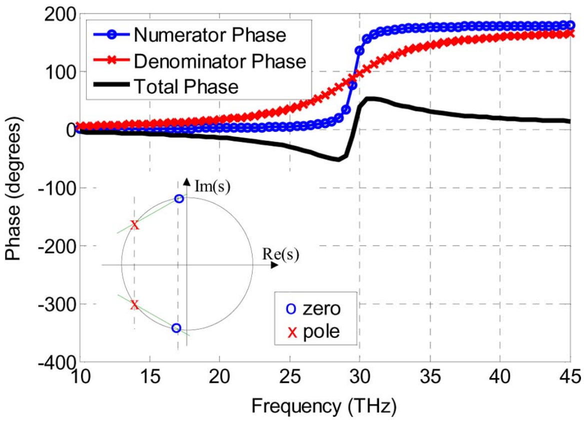


Fig. 8. Reflection coefficient analysis for the high loss case $(\mathrm{R} < \mathrm{Z}_\mathrm{o})$. The positions of poles and zeros in the S-plane, and the corresponding phase versus frequency.

In this case the zeros of the function are on the imaginary axis in the S-plane. At the resonance frequency the reflection coefficient will be zero $(|\Gamma(\mathrm{S})| = 0)$, i.e., a total loss and no reflected power.

When $\mathrm{R} < \mathrm{Z}_0$ the zeros will be located on the left side of the S-plane, as shown in Fig. 8. The positions of the poles and zeros indicate that in this case although the magnitude of the reflection coefficient is non-zero it will have a phase range below 180°. This means that when the losses in the unit-cell go beyond the critical limit $(\mathrm{R} = \mathrm{Z}_0)$, not only the reflected power but also the phase range will be insufficient for reflectarray unit-cells.

C. Discussions

Based on the previous investigation, it is clear that the low loss reflectarray element design, which is not a major concern at the microwave frequency, becomes a critical topic at the optical frequency. The element loss results from the finite value of the metal conductivity and high loss tangent of the dielectric substrate, and becomes severe near the resonant frequency. Some conventional element design methods in the microwave frequency such as variable-size patches may suffer from significant losses, and new design methodologies need to be developed.

In traditional reflectarray antennas, both conductors and dielectrics are used in element designs. The comparison of metallic and dielectric loss influence does not have a definite answer, but rather depends on particular selections of metal and dielectric in an individual reflectarray design. At THz/optic frequencies, the dielectric loss may be minimized by selecting proper materials such as BCB, but the conductor loss is a major concern. Using high quality conductors such as gold, significantly reduces the losses, however this runs contrary to the goal of a low-cost system. Low-cost conductors such as aluminum on the other hand have a higher loss, which will decrease the efficiency of the system. In addition while these low-cost conductors may achieve a complete phase range in the far-infrared range, at the short- and near-infrared range they will suffer from a limited phase range which will further reduce the efficiency of the system.

A possible solution is to use resonant dielectric elements in reflectarray designs. The idea is similar to the dielectric resonator antenna (DRA) concept in microwave and millimeter wave designs [26], [27]. A dielectric cavity backed by a conducting ground plane will be designed as the reflectarray phasing element. The phase control will be realized by the proper design of the shape and dimensions of the dielectric resonator, hence avoiding the use of a resonant conductor patch. This dielectric resonant element approach has some resemblance to the fiber optic design except that the cavity structure is designed instead of the transmission line structure.

V. CONCLUSION

Infrared reflectarray antennas are investigated in this paper, with a focus on the element loss mechanism. Electromagnetic properties of some conventional IR materials are reviewed for the reflectarray element designs. The conductor and dielectric loss effects on the reflection magnitude and phase of the reflectarray elements are demonstrated through full wave simulations. A circuit model of the unit-cell was used to understand the loss effects and reflection coefficient behaviors. It is shown that as a result of the resonance phenomenon, when the material loss increases and the equivalent resistor matches the wave impedance in space, total loss of power occurs. As the material losses increase beyond this point, a new reflection curve with a narrow dynamic phase range is observed. Based on these investigations, dielectric resonant elements using low loss tangent materials are suggested for future infrared reflectarray designs. The low loss optical reflectarrays have many potential applications, such as the highly efficient concentrating solar power systems.

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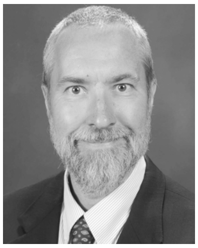
Dr. Shelton is a former NSF IGERT fellow.



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