Salisbury screen absorbers using epsilon-near-zero substrate

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Abstract

As a planar resonant structure, Salisbury screen offers a cost-effective way of manipulating electromagnetic waves for both fundamental studies and practical applications in optoelectronics. In this paper, we demonstrate Salisbury screen absorbers using epsilon-near-zero substrate, which reduces the spacer thickness below typical one quarter wavelength limit. Three-layered thin-film absorbers made of SiC substrate, ZnSe spacer layer and top NiCr film are designed and fabricated, which exhibit near-perfect absorption at 11.72 μm with spacer thickness of about half of a quarter-wavelength. For ideal zero-index material without optical loss, our proposed thin-film absorber simplifies to a two-layered structure even without the spacer layer in theory. These results suggest that epsilon-near-zero materials provide an alternative approach in developing compact planar absorbing structures without involving lithographic patterning.

1. Introduction

Salisbury screen, consisted of an absorptive film placed a quarter-wavelength distance above a reflecting plane, is a classical electromagnetic structure for controlling wave absorption and reflection. Salisbury screen was originally invented in the microwave region, where both single-band and broadband perfect absorptions were demonstrated for effectively reducing radar cross section [1, 2]. Due to its simplicity in structure and versatile functionalities, Salisbury screen has recently also attracted considerable interest at optical frequencies. By designing different material combinations at impedance-matching condition, multilayered Salisbury screens were developed across a wide spectral range at infrared and visible wavelengths with many interesting properties such as perfect light absorption [3–5], strong thermal emission [6, 7] as well as dynamic spectral tunability [8, 9], which are of potential use in infrared camouflage, photodetection and energy harvesting [10–13]. In addition, Salisbury screen was also applied in engineering optical properties of emerging two-dimensional materials. For example, significantly enhanced light absorbance was demonstrated in monolayer graphene using the Salisbury screen configuration [14–16]. For these three-layered Salisbury screens, their spacer layer thickness is at least one quarter wavelength, which presents a limitation in terms of device sizes and complexity. Patterned plasmonic antennas in the geometry of metal-insulator-metal (MIM) structure offer a pathway to overcome this one quarter wavelength limit, although they often require complicated lithographic fabrications [17–20]. Recently, based upon resonant destructive interference with special interface reflection phases, simplified two-layered thin-film absorbers were demonstrated in the systems of a phase-change VO₂ film [21, 22] or a semiconducting film [23–26] on substrates made of metal, sapphire or highly-doped semiconductor.

In this work, we propose to use epsilon-near-zero (ENZ) substrate to overcome the quarter-wavelength thickness limit in Salisbury screen absorbers. Three-layered absorbers with SiC substrate instead of conventional metal plane are designed and fabricated. A near perfect absorption of 99% is realized at the wavelength of 11.72 μm with spacer thickness of about half a quarter wavelength. These results open an alternative pathway in developing compact thin-film absorbing structures based upon the unique properties of ENZ materials.
2. Design and simulation

The structure of our designed thin-film absorber is sketched in figure 1(a), which consists of a SiC substrate, a ZnSe spacer layer and a top NiCr film of thickness $d_1 = 5$ nm. In contrast to conventional Salisbury screen using metallic substrate, an ENZ material SiC is used instead. SiC is a known polar dielectric with ENZ response in the mid-infrared spectral band $[27–29]$. As shown in figure 1(b), in the wavelength region between 10.3 and 12.5 μm, the real part of its refractive index is nearly zero, while the imaginary part of its refractive index is moderately small. This ENZ property of SiC leads to special light reflection phase, which is utilized in designing our Salisbury screen with reduced spacer layer thickness. Light absorption in such three-layered structure is facilitated by resonant destructive interference as determined by the phase relationship $[30]$

$$\frac{4\pi n_2 d_2}{\lambda} + \Delta \varphi = 2\pi j \quad (j = 0, 1, 2...)$$

where $\lambda$ is the free-space wavelength, $d_2$ is the thickness of the ZnSe layer, $n_2$ is the refractive index of ZnSe, and $\Delta \varphi$ is the phase shift upon reflection from ZnSe to the SiC substrate. For conventional Salisbury screen with a metal substrate, the phase $\Delta \varphi$ is $\pi$, which leads to a spacer thickness of a quarter wavelength, i.e. $d_2 = \lambda/(4n_2)$ $[1, 31]$. Here for our design with SiC as the substrate, the phase $\Delta \varphi$ deviates from $\pi$ as a result of the special ENZ property, which enables a mechanism to reduce the ZnSe thickness to less than a quarter wavelength. Figure 1(c) shows the detailed phase $\Delta \varphi$ and amplitude $|r|$ of reflection coefficient at the interface between ZnSe and SiC. The reflection amplitude exceeds 0.85 in the band of 10.6–12.5 μm, acting as a reflective mirror like normal metal substrate. Meanwhile its phase shift is larger than $\pi$, decreasing from $1.7\pi$ to $\pi$ within the ENZ region. This larger than $\pi$ reflection phase leads to a reduced propagating phase $4\pi n_2 d_2/\lambda$ within the spacer layer at the resonant condition of fundamental mode with $j = 1$, and thus a less than one quarter wavelength thickness $d_2$ is possible for a given wavelength.

Based on the above resonance phase consideration, we designed the absorber structure using both transfer matrix method and numerical rigorous coupled-wave analysis (RCWA) method. Refractive index of the ZnSe is assumed to be $n_2 = 2.42$ $[32]$, and that of the NiCr film is described as $n_1 = 3.61\sqrt{\lambda} + 3.61\sqrt{\lambda}$, as given in $[33]$. For a target center wavelength of $\lambda = 11.24$ μm, the perfect absorption is obtainable at ZnSe thickness of $d_2 = 620$ nm, which is about half a quarter wavelength, i.e. $\lambda/(7.5n_2)$. Figure 1(d) shows the calculated spatial intensity distributions of optical field inside the structure with $d_2 = 620$ nm at first order resonant condition ($j = 1$).
Figure 2 shows our calculated absorption spectra of the Salisbury screen absorbers with SiC substrate. For the designed spacer thickness of 620 nm, a near 100% absorption peak is obtainable at 11.24 μm in the ENZ region, which validates the effectiveness of using ENZ substrate for reducing spacer thickness in Salisbury screen. In addition, as the spacer thickness varies, the peak absorption wavelength shifts as a result of the changed resonant condition described in equation (1). Figure 2(b) shows the resonant peak absorption wavelength as a function of the ZnSe spacer thickness. It is seen that the peak wavelength increases with the spacer thickness, which is always less than a quarter wavelength as in the case of a metal substrate shown in black dashed line. As the wavelength decreases from 12 μm to 10 μm, the spacer thickness becomes more reduced as relative to the quarter wavelength value. This trend originates from the increasing reflection phase shift towards shorter wavelengths as given in figure 1(c).

3. Experimental results and analysis

To validate our proposed Salisbury screen absorber with reduced spacer thickness, we fabricated the structure using electron beam evaporation technique. First a ZnSe film was deposited on a commercial SiC substrate, and then a thin layer of NiCr film was deposited on top of the ZnSe. To obtain optimal perfect absorption, we fabricated samples with different ZnSe and NiCr film thicknesses. The film thickness of the ZnSe layer was measured using ellipsometry measurements and that of the NiCr layer was obtained with scanning electronic microscopy (SEM) images. Figure 3 shows a cross sectional SEM image of a representative sample with 633 nm ZnSe and 44 nm thick NiCr.

The fabricated Salisbury screen absorbers were characterized with Fourier transform infrared reflection (FTIR) spectroscopy [34]. The sample and the detector were mounted on two coaxial rotation stages, which allows for transmission measurement or reflection measurement at a minimum incident angle of 15°. A broadband infrared light from the FTIR spectrometer was focused by an 8-inch focal length off-axis parabolic
mirror onto the sample with a spot size of about 1.5 mm. The reflection from a copper mirror was used as the reference spectrum in reflection measurement, and light transmission through open air was used as the reference spectrum in transmission measurement. Absorption spectrum was obtained by subtracting the reflection and transmission coefficients from one.

Figures 4(a)–(c) show the measured reflection, transmission and absorption spectrum of the sample with 633 nm thick ZnSe and 44 nm NiCr. There is reflection dip at 11.72 μm wavelength with nearly zero reflectance. Meanwhile as the transmission is near zero within our measured spectral range, a near perfect absorption of 99% is obtained at 11.72 μm. These measured results are in general agreement with our simulated spectrum with \( d_z = 633 \) nm in figure 2(a). There are some minor deviations in spectral shape, which are caused by variations of film thickness and material property between experiment and simulation, especially about the NiCr film. Our fabricated NiCr thickness is 44 nm, which is significantly larger than the designed value of 5 nm. To investigate this factor, we fabricated Salisbury screen samples with different NiCr thicknesses. The ZnSe spacer layer is 633 nm thick for these samples. Their measured absorption spectra are shown in figure 4(d). For an 11 nm thick NiCr, the sample exhibits a resonant absorption peak at 11.27 μm, which closely matches the resonant wavelength in design with 5 nm NiCr. However, the measured peak absorption is only 56%, much less than the expected perfect absorption value. As the NiCr increases in thickness, the peak absorption gradually increases and reaches 99% at 44 nm thickness. Besides the increased peak absorption, the peak wavelength also slightly redshifts as the NiCr thickness increases. This absorption shift is likely caused by the extra phase shift occurring within the NiCr layer, which is normally ignored in typical three-layered Salisbury screen like described with equation (1). Therefore, the obvious difference of NiCr thickness between theory and experiment is likely caused by the deviation of optical constants of fabricated NiCr film from theoretical model.

To gain a better understanding on the absorption property of our demonstrated Salisbury Screen using SiC, we measured absorption spectra of the structures with and without top NiCr film. From figure 5(a), we see that the sample without NiCr film exhibits very small absorption of about 7.4% within the ENZ wavelength range between 10.3 and 12.5 μm, while the sample with top NiCr film has near-perfect absorption at 11.72 μm. This comparison suggests that majority of the absorption occurs within the NiCr layer. On the condition of resonant destructive interference without reflected energy, the light is trapped and bouncing back and forth between the two surfaces of the spacer layer. Since the top NiCr is significantly more lossy than the SiC substrate, most of the light energy is dissipated by the NiCr film during multiple round-trip light travels. We note that subtraction of the two absorption spectra in figure 5(a), however, cannot give an accurate estimation on the absorption of the top NiCr layer, as the impedance and light path are different for the two structures with and without NiCr film. We therefore calculated the absorption of each layer of our designed Salisbury Screen (structure given in

![Figure 4. Measured (a) reflection, (b) transmission and (c) absorption spectrum of the Salisbury screen sample with 633 nm thick ZnSe spacer layer and 44 nm NiCr absorptive layer. (d) Absorption spectra of Salisbury screen samples with different NiCr thicknesses.](image-url)
figure 1(a)) using the numerical RCWA model. As revealed in figure 5(b), the NiCr layer absorbs 91.6% of the light at the resonant wavelength of 11.24 μm, while the remaining 8.4% is absorbed by the SiC substrate.

In our above experiments, we used SiC as an ENZ material to validate our proposed Salisbury screen. In fact, for ideal zero-index materials, the three-layered Salisbury screen absorber could be reduced to a two-layered structure without the spacer layer. This scenario is illustrated in figure 6(a). For ideal zero-index materials with zero real and imaginary parts of refractive index, its reflection amplitude |r| is 1 and its phase Δφ is 0 as shown in figure 6(b). This zero reflection phase, according to resonant condition of equation (1), leads to a zero thickness (d2 = 0) of the ZnSe spacer layer at the resonance condition with j = 0. Therefore, a two-layered system with absorptive NiCr on top of zero-index substrate enables perfect absorption. Figure 6(c) shows the optical field distribution at the surface of an ideal zero-index substrate at resonant condition according to resonance condition with j = 0. To avoid non-converging problem in this field calculation, we used a sufficiently small refractive index value of 0.01 for the zero-index substrate [35, 36]. It is seen that the field is enhanced by a factor of 2 at surface of the substrate within the entire spectral band, which enables a strong interaction with the absorbing NiCr film. Its calculated absorption exhibits 100% efficiency across the whole wavelength range as shown in figure 6(d), where the NiCr film was assumed to be 5 nm thick. This two-layered absorber exhibits a large bandwidth, which is likely preferred in broadband applications. Its experimental demonstration would require innovations in the development of zero-index materials, as existing bulk or nanostructured zero-index materials are all narrow band and inherently have some optical losses [37]. J M Pérez-Escudero et al. recently demonstrated a two-
layered absorber made of a Ti film on SiC substrate [38], which exhibited pronounced absorption enhancement within a finite bandwidth as limited by the ENZ dispersion of SiC.

4. Conclusions

In summary, we have designed and demonstrated Salisbury screen absorbers using SiC as the substrate, whose special ENZ response was utilized to reduce the spacer thickness below typical one quarter wavelength limit. Three-layered absorbers comprised of SiC substrate, ZnSe spacer layer and NiCr absorbing film were designed and fabricated, which exhibited a near perfect absorption of 99% at wavelength of 11.72 μm with spacer thickness of about half a quarter wavelength. In addition, we also analyzed the case of ideal zero-index substrate without optical loss, which simplified the three-layered absorber to a two-layered structure with broadband perfect absorption character. These results indicate that ENZ material offers an appealing scheme for developing compact cost-effective thin-film absorbing structures.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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