FREE-SPACE WIDE-APERTURE SHEET-ISOLATOR BASED ON A MULTILAYERED RESONANT CAVITY

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ABSTRACT

We introduce a nonreciprocal multilayered structure (a stack) acting as a free-space thin-sheet optical/microwave isolator with unlimited aperture and the possibility of a broadband omnidirectional rejection of the light incident on the back interface of the stack. The light normally incident on the front interface displays a strong resonant transmittance. The entire stack involves a subwavelength magnetic layer, misaligned dichroic nanolayers, and an optional metallic nanolayer, all incorporated in a low-loss multilayered resonant cavity. The (optional) metallic nanolayer provides a broadband omnidirectional rejection of the light incident on the back interface of the stack. Preliminary experimental results for the W-band and X-band illustrate how the key elements of the design work. The same design can be scaled down to long- and even mid-infrared wavelengths.

1. INTRODUCTION

Optical isolators transmit light only in one of two opposite directions. They are indispensable in numerous optical and microwave applications [1–8]. A typical free-space isolator comprises a 45-degree Faraday rotator (FR) placed between a pair of linear polarizers (LSP1 and LSP2) with 45-degree misalignment, as schematically shown in Fig. 1 [9]. The existing free-space isolators have certain inherent problems, one of which is a limited aperture. In this paper we explore the possibility of a (multilayered) sheet-isolator with virtually unlimited aperture. The latter requirement implies that both polarizers LSP1 and LSP2 in Fig. 1 should also be sheet-polarizers, as opposed to beam-splitting polarizers. A fundamental problem with the existing dichroic sheet-polarizers is that they only partially absorb the input light component with unwanted linear polarization, while the rest of it is reflected [10,11]. The partial reflectivity of the unwanted linear polarization will inevitably result in a failure of the sheet isolator. Indeed, the backward propagating input light (the one that should be blocked by the isolator), after entering the system through the polarizer LSP2 in Fig. 1b, will bounce back and forth between the two polarizers, every time passing through the Faraday rotator and acquiring additional 45-degree Faraday rotation. After two bounces, the light will return to the polarizer LSP1 with additional 90-degree polarization rotation and, thus, will not be blocked by the polarizer LSP1. The latter amounts to isolation failure. To prevent the backward propagating input light from passing through the sheet-isolator, we must make at least one of the two polarizers perfectly absorptive for the unwanted linear polarization, thereby, preventing the backward propagating input light from bouncing back and forth between the two polarizers. Designing perfectly
absorptive sheet polarizers and incorporating them into the multilayered sheet isolator is the focus of our investigation.

In Section 2 we introduce different sheet polarizers involving dichroic nanolayer(s) incorporated into the low-loss resonant cavity, shown in Fig. 2a. The calculated transmission dispersion of the resonant cavity (without dichroic nanolayers) is shown in Fig. 2c. The field distribution at the frequency of resonant transmission is shown in Fig. 2b.

The addition of one or more (aligned) ultra-thin dichroic nanolayers to the resonant cavity does not affect the propagation of light with the allowed linear polarization (hereinafter, the TM polarization) – the resonant field distribution and the transmission dispersion remain nearly the same as those shown in Figs. 2b and 2c for the case of the resonant cavity without the dichroic nanolayers. What happens to the undesired polarization component (hereinafter, the TE polarization) strongly depends on the location of the dichroic nanolayers in the resonant cavity. For instance, in the simplest symmetric configuration shown in Fig. 3, the incident light with the TE polarization is nearly totally reflected. By contrast, in the more complex, but still symmetric configuration shown in Fig. 4, the input light with the undesired TE polarization experiences a nearly total resonant absorption at the frequency of the cavity resonance. Finally, in the asymmetric configuration shown in Fig. 5, the light with the undesired TE polarization experiences either strong broadband reflectivity (for the forward direction of incidence), or strong resonant absorption (for the backward direction of incidence), as shown in Fig. 5c. In all cases shown in Figs. 3 – 5, the input light with the undesired TE polarization is blocked, while the light with the allowed TM polarization displays a strong resonant transmittance. Away from the frequency of cavity resonance, all the sheet polarizers in Figs. 3 – 5 reflect both the forward and backward propagating light regardless of its polarization. Note that since the polarizers LSP1 and LSP2 in Fig. 1 are misaligned, the definition of TE (or TM) polarization is polarizer dependent.

As was pointed out in the first paragraph of the Introduction, the backward propagating wave passed the Faraday rotator in Fig. 1 must be absorbed by the dichroic sheet polarizer – not reflected back toward the Faraday rotator. The symmetric absorptive configuration in Fig. 4 and the asymmetric reflective/absorptive configuration in Fig. 5, both satisfy the above requirement and thus can be used as components of a sheet isolator. Indeed, the high reflectivity of the TE-
polarized light incident on the front interface of the asymmetric polarizer (the red arrows in Fig. 5) will not compromise the isolator performance. Moreover, the high reflectivity in the latter case will enhance the power capability of the sheet isolator by preventing overheating of the input polarizer LSP1. At the same time, the TE-polarized light incident on the back interface of the asymmetric polarizer (the green arrows in Fig. 5), does experience nearly perfect resonant absorption, which is essential for the sheet isolator in Fig. 1 to function properly.

As a proof of concept, we fabricated and tested the asymmetric resonant sheet polarizer described above. The detailed description of the design and the experimental results are presented in Section 3. Although it is designed for the W-band, our approach is highly scalable, and can be replicated at any frequency range starting from microwave, and up to mid-infrared. At shorter wavelengths, the biggest challenge is not so much with the absorptive sheet-polarizers, but rather with thin enough Faraday rotators.

Another fundamental problem associated with the existing free-space isolators is that they fail to stop the light obliquely incident on the back interface. Indeed, at oblique incidence, the backward propagating light transmitted by the polarizer LSP2 in Fig. 1 and subsequently by the Faraday rotator, will acquire elliptic polarization and, thus, will not be completely blocked by the polarizer LSP1. One way to address this problem and to make the sheet isolator omnidirectional is to add a metallic nanolayer to the multilayered sheet-isolator. The location of the metallic nanolayer should coincide with the nodal plane of the electric component of the resonant field distribution. At normal incidence, such a nanolayer is "invisible" for the resonant mode and does not interfere with the resonant transmittance of the allowed linear polarization. At oblique incidence, though, the nodal plane of the electric field distribution shifts away from the metallic nanolayer, and the entire multilayered structure becomes highly reflective at any frequency. For this to happen, the nodal plane location must not coincide with the local symmetry plane (if any) of the multilayered structure. The detail description of this approach can be found in [12]. In the case considered in [12], the metallic nanolayer was ferromagnetic and, thus, it provided not only rejection of obliquely incident light, but also the 45-degree Faraday rotation for the light with normal incidence. In this paper, we will not further elaborate on the problem of oblique incidence.

Fig. 1 presents a traditional intuitive design of a free-space isolator based on a 45-degree Faraday rotator sandwiched between a pair of misaligned polarizers. As we already mentioned, in the case of a wide-aperture sheet isolator, the sheet polarizers must absorb (not reflect) the undesired polarization component of the light passed the Faraday rotator. In Section 3 we present an example of a generalized, integrated sheet isolator. The integrated design still involves dichroic and magnetic layers incorporated in a low-loss multilayered cavity, but now the polarizers cannot be identified as distinct parts of the entire multilayered structure. Such an integrated design can be simpler and more efficient than the traditional design with the distinct Faraday rotator and polarizers.
2. EXAMPLES OF SHEET POLARIZERS WITH NEARLY TOTAL RESONANT ABSORBANCE OR REFLECTANCE OF THE REJECTED INPUT LIGHT POLARIZATION

In our simulations, we consider three different layered structures, shown in Figs. 3 – 5; each involves one or more aligned dichroic nanolayers imbedded in the lossless resonant cavity in Fig. 2a. All the dichroic nanolayers are identical. For the TM-polarized light, the dichroic nanolayers are virtually invisible, due to their small thickness. For the TE-polarized light, the number and the location of the dichroic nanolayers inside the lossless host-cavity make a huge difference. In our simulations, the dichroic nanolayers have a negligible thickness and highly anisotropic sheet impedance: \( Z_x = \infty \) and \( Z_y = 2.545 \ \Omega/m^2 \). A stand-alone dichroic nanolayer transmits the \( x \)-polarization component of the incident wave without reflection or absorption, while mostly reflecting the \( y \)-polarization component. The respective transmittance and reflectance are 

\[ T_x = 1, \ R_x = 0, \quad \text{and} \quad T_y = 1.79 \times 10^{-4}, \ R_y = 0.973. \]

The high reflectivity of the \( y \)-polarization component does not allow to use a stand-alone dichroic nanolayer as a polarizer in a sheet-isolator.

The lossless resonant cavity in Fig. 2a involves a half-wave defect layer located in the middle of a periodic stack of alternating quarter-wave layers with the high (H) and the low (L) dielectric constant. The entire configuration can be described as \((HL)^4(LH)^4\). The constitutive layers of the resonant cavity have the respective dielectric constants of \( \varepsilon_H = 9.5 \) and \( \varepsilon_L = 3.8 \), which corresponds to the actual materials used in our experimental measurements (see the next section). The quarter-wave layers thicknesses are 

\[ d_H = \frac{\lambda_0}{4\sqrt{\varepsilon_H}} \quad \text{and} \quad d_L = \frac{\lambda_0}{4\sqrt{\varepsilon_L}}, \]

respectively. The half-wave defect layer provides a quasi-localized mode associated with the resonant transmittance at the mid-gap wavelength of \( \lambda_0 \). Since the half-wave defect layer has the low
refractive index, the resonant field distribution shown in Fig. 2b has antinodal plane in the middle of the defect layer, where the amplitude of the quasi-localized resonant mode reaches its maximum value. In our simulations we use the quarter-wave layer thicknesses of $d_H = 255.9 \, \mu m$ and $d_L = 404.7 \, \mu m$, in which case the frequency of resonant transmittance is 95 GHz.

The simulated transmittance/reflectance dispersion for the lossless resonant cavity in Fig. 2a are shown in Fig. 2c. The spatial intensity distribution of the electric field component within the cavity at the resonance frequency of 95 GHz is shown in Fig. 2b. In the absence of the dichroic nanolayers, the results presented in Figs. 2b and 2c are polarization independent. In the presence of the dichroic nanolayer(s) described earlier in this section, the results in Figs. 2b and 2c still apply, but only to the case of x-polarized incident wave. In this setting, the x-polarization coincides with the allowed TM polarization, while the y-polarization coincides with the TE polarization – the one that should be blocked by the polarizer.

The addition of the dichroic nanolayer(s) with $Z_x = \infty$ to the resonant cavity only affects the incident light with the TE polarization, providing a broadband, omnidirectional, and strongly enhanced transmittance suppression. What happens to the rejected polarization component of the input light, however, strongly depends on the number and the location of the dichroic nanolayers in the cavity. In our simulations, we will limit ourselves to the case of normal incidence. The case of oblique incidence is briefly discussed in section 4.

Let us start with the symmetric configuration in Fig. 3a, where the sole dichroic nanolayer coincides with the symmetry plane of the cavity. The simulations show that the resonant transmittance T of the y-polarization component drops to $10^{-7}$, which is by three-orders-of-magnitude lower, compared to the stand-alone dichroic layer. The reflectance R approaches unity (as seen in Fig. 3c), while the absorbance drops by an order-of-magnitude, compared to the stand-alone dichroic layer. The physical reason for the reduced absorption is that the y-polarization component is mostly reflected from the Bragg-reflector part of the LSP and that the electric field intensity at the dichroic layer is only about one per cent of the incident wave
intensity, as seen in Fig. 3b. The decreased absorption can drastically reduce the absorption-related heating and, thereby, significantly increase the power-handling capability of the LSP. On the down side, the high reflectance of the TE-polarized wave makes it impossible to use the sheet-polarizer in Fig. 3b as a component of the sheet-isolator.

If, on the other hand, the dichroic layer is positioned at the nodal plane of the resonant electric field distribution, the resonant absorptance of the y-polarized wave can be greatly enhanced. However, the absorptance of an ultrathin homogeneous layer is known not to exceed 0.5 (see, for example, [13]). This absorptance limit can be overcome in a patterned thin film with an intrinsic resonance, such as a plasmon resonance [13,14], magnetic resonance coupling [15] or by using the Salisbury screen, which is a highly reflective surface positioned at a quarter-wave distance behind an absorbing layer [16,17]. The latter also refers to “coherent perfect absorption (CPA)” [18–21] and “critical coupling” [22–26].

In the LSP of Fig. 4b, we utilize, as a reflecting screen, the additional dichroic nanolayer positioned in the middle of the LSP, resulting in nearly perfect absorption of the y-polarization at the resonance frequency. The third dichroic layer has been added for symmetric operation, so that the LSP equally absorbs the y-polarization component of the wave incident from either direction. The resonant transmittance $T$ of the y-polarized wave drops now to $10^{-8}$, implying a huge enhancement of the polarization extinction ratio. The reflectance and absorbance dispersion are shown in Fig. 4c. The nearly perfect absorbance of the y-polarized wave is narrowband, due to its resonant nature. In the vicinity of the cavity resonance, this sheet polarizer can be used as a component of the resonant sheet-isolator. Away from the resonance frequency, all the multilayered structures shown in Figs. 2 – 5 are highly reflective, regardless of the incident light polarization.

If the left dichroic nanolayer of the LSP in Fig. 4 is removed, the structure becomes asymmetric, as shown in Fig. 5. The scattering characteristics for the y-polarized wave also become extremely asymmetric. Of course, due to the reciprocity principle, the transmittance

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**Fig. 4:** (a) Schematics of the absorptive LSP involving three dichroic layers (black) incorporated into the host structure of Fig. 2a. (b) Simulated spatial intensity distribution, $|E(z)|^2$, of the TE polarization component at 95 GHz. (c) Simulated dispersion spectra of the absorptance (A) and reflectance (R) of the TE polarization component.
remains perfectly symmetric. In particular, the resonant transmittance of the y-polarized wave remains below $10^{-7}$, implying a huge enhancement of the polarization extinction ratio of the asymmetric sheet polarizer in Fig. 5. What is new now is an extremely strong asymmetry in reflectance and absorbance, shown in Fig. 5c. At the frequency of cavity resonance, the forward-propagating y-polarized wave is reflected by the asymmetric LSP in Fig. 5, while the backward propagating y-polarized wave is nearly totally absorbed, mostly by the right dichroic nanolayer. Note that the Salisbury screen, which is inherently asymmetric, can also produce strongly asymmetric absorption/reflection of the incident wave at a resonance frequency [16]. It will, however, have the polarization extinction ratio and power limitations of a common dichroic sheet polarizer. By comparison, in the case of LSP presented in Fig. 5, both polarization extinction ratio and power-handling capabilities can be greatly enhanced.

3. EXPERIMENTAL REALIZATION OF THE ASYMMETRIC RESONANT LSP

Here we report millimeter-wave measurements of the LSP with strongly asymmetric absorption/reflection of the undesired (TE) polarization. The LSP was assembled from C-cut sapphire and fused quartz wafers, and aluminum (Al) wire grids deposited on sapphire wafers. The LSP structure is $(S_1Q_1)^2(S_1Q_2)(GS_2)^2(Q_2S_1)(Q_1S_1)^2$, where $S_1$ and $S_2$ are 256-µm and 246-µm sapphire, $Q_1$ and $Q_2$ are 404-µm and 442-µm quartz, respectively, and $G$ is a 40-nm thick Al wire grid with a duty cycle of 0.3 and periodicity of 20 µm. The design of the LPS was by no means optimized due to limited stock of wafers at the time of assembly.

The wire grid on sapphire (GS$_2$) was measured with a normally incident gaussian beam in the forward and backward directions. The S-parameters of GS$_2$ were measured with the use of a Keysight vector network analyzer. We observed no difference between the results obtained for the beams incident in the forward and backward directions, within experimental error. The T and R spectra of the wire grid oriented along the y-axis are shown for the x- and y-polarizations of
the incident wave in Fig. 6a and b, respectively. The position of Fabry-Perot resonance of the substrate is indicated by the sharp dip in reflectance R of the x-polarized wave in Fig. 6a. In the vicinity of the resonance, the polarization extinction ratio of the wire grid is about 33 dB. For the rejected y-polarization, the reflectance R is only 0.86, implying that the wire grid still has a significant absorption, \( A \approx 0.14 \).

The same measurements of the S-parameters were carried out for the asymmetric LSP with wire grids being oriented along y-axis. The T and R spectra for the x-polarized wave are shown on Fig. 7a; the difference between the forward and backward directions of incidence in negligible, similar to the case of GS2. The LSP supports perfect resonant transmittance for x-polarization at 94.4 GHz and is highly reflective away from the resonance, indicating that the grids do not interact with x-polarization component of the radiation. By comparison, the absorbance/reflectance of the y-polarized wave is highly asymmetric, due to its strong interaction with the aluminum grids, as shown on Fig. 7b and 7c. These experimental results are qualitatively identical to the results of our simulations, reflected in Fig. 5c.

For the forward propagated y-polarized wave measured reflectance R reaches 0.99 at the vicinity of the resonant frequency of 94.4 GHz and transmittance T is suppressed down to -50dB within the entire band gap. This implies that absorptance A of the wave traveling in forward direction is smaller than 0.01. By contrast, for the backward propagated y-polarized wave, the measured reflectance R shows extremely sharp -38 dB dip at 94.03 GHz, with transmittance T being absolutely the same as in the case of forward propagated wave. This indicates that for the y-polarization component of the wave traveling in backward direction the experimental LSP is almost completely absorptive at the resonant frequency.

Note that the Fabry-Perot resonant frequency for the y-polarization incident in backward direction is red-shifted to 94.03 GHz from 94.4 GHz, which can be seen from the difference in position of reflectance R dip in Fig. 7a and 7c. This is attributed to the reactance of the wire grids, which makes their optical thickness for y-polarized component large enough to produce a measurable shift. This effect can be further reduced by lowering periodicity of the grid from 20 \( \mu \)m down to few microns. Demonstrated mm-wave LSP exhibit a large 50dB extinction ratio.
The degree of reflection asymmetry for y-polarized light is about 5000 at the resonant frequency. In comparison with stand-alone dichroic nanolayer, the asymmetric LSP offers 20dB higher extinction ratio and significantly enhanced power capabilities (for the forward propagating wave). Also, according to our measurements, if light is incident on the LSP at oblique incidence, its performance will not be significantly affected, as long as the angle of incidence does not exceed 40-degree. The oblique incidence, though, results in a blue-shift of the resonant frequency, which provides ability to tune the operational frequency by tilting the LSP.

4. INTEGRATED LAYERED SHEET ISOLATOR

The most straightforward way to build a sheet isolator is to place a thin-sheet Faraday rotator between a pair of misaligned sheet polarizers, as schematically shown in Fig. 1. Possible designs of sheet polarizers are described in Figs. 4 and 5 and experimentally tested at the W-band frequencies. A possible design of a resonant thin-sheet Faraday rotator for microwave frequencies was discussed in [12], where a ferromagnetic (cobalt) nanolayer was placed in a nodal plane of the electric component of the quasi-localized mode in a multilayered resonant cavity. Such a configuration allows to drastically suppress the Ohmic losses caused by the cobalt electric conductivity while, dramatically enhancing the magnetic Faraday rotation. The latter effect is explained as follows. At microwave frequencies, the Faraday rotation is caused by the interaction of oscillating magnetic field with the ferromagnetic material (say, cobalt). Since the nodal plane of the resonant electric field distribution coincides with the antinodal plane of the oscillating magnetic field, we simultaneously have a strong suppression of the Ohmic losses, and a strong enhancement of magnetic Faraday rotation [12]. For infrared wavelengths, we might have to use a different Faraday rotator design. In any case, the whole assembly involves three resonant cavities: one hosting the magnetic or magneto-optical layer, and another two related to the pair of resonant sheet polarizers. All three cavities must have the same resonant frequencies.

Here, we suggest the idea of utilizing the same resonant cavity to host the dichroic nanolayers and the magnetic nanolayer responsible for the Faraday rotation. In this case, the polarizers
cannot be identified as separate components of the entire stack. Such an integrated design can be seen as an optimized version of the layered sheet-isolator. A numerical example of the integrated sheet-isolator design is presented in Fig. 8. The resonant millimeter-wave cavity is composed of low-loss quartz and sapphire quarter-wave layers. The cavity hosts both magnetic and dichroic layers. The Faraday rotation is provided by a 9.3-µm thick strontium ferrite layer with the permittivity $\epsilon = 6 + 0.55i$ [27] and Verde constant $\nu = 1530 \text{ rad/T·m}$ [28], in a bias magnetic field of 540 mT. The dichroic components are presented by two pairs of 9-nm thick aluminum wire grids with a duty cycle of 0.2. According to our simulations, the integrated sheet-isolator provides the forward resonant transmittance with insertion loss of 3 dB (Fig. 8b, red line). At resonance frequency of 94.37 GHz, the isolation ratio is about 40 dB (Fig. 8b, green line). Away from the resonance, the entire multilayered structure is highly reflective in either direction.

The integrated sheet-isolator in Fig. 8 supports resonant transmittance for the forward y-polarized incident wave. Dichroic nanolayers in this case do not affect the propagation of the y-polarized wave incident on the front interface (propagating in the forward direction). The x-polarization component of the wave incident on the front interface will not enter the multilayer and will be reflected. The portion of the wave incident on the back interface (propagating in backward direction) that passes through the right-side set of dichroic nanolayers and the
magnetic layer, will be subsequently absorbed by the dichroic nanolayers on the left-hand side of the magnetic layer, as clearly seen in Fig. 8d. At the resonant frequency, the isolation ratio of the integrated sheet-isolator in Fig. 8 is predicted to be as high as –40dB.

5. CONCLUSION

In conclusion, let us reiterate that the proposed wide-aperture sheet isolators are based on a low-loss resonant cavity hosting subwavelength dichroic nanolayers and a magnetic layer with normal magnetization. The forward transmittance of a sheet isolator is essentially narrowband, due to its resonant nature. The role of the cavity resonance is essential and multifold. Firstly, the resonance enhances the magnetic Faraday rotation produced by a subwavelength magnetic layer, thereby allowing to make the sheet isolator rather thin – its total thickness does not exceed a few wavelengths. Secondly, the resonant conditions allow the use of thin dichroic nanolayers by enhancing/modifying their dichroic properties. In particular, the resonant conditions provide a nearly total (resonant) absorption of the backward propagating light by the dichroic nanolayers, thereby, preventing the sheet isolator from failure. The same dichroic nanolayers taking away from the multilayered resonant cavity would be mostly reflective and, thus, could not be used in a sheet isolator. Finally, the resonant conditions are necessary for the formation of a quasi-nodal plane in the oscillating electric field distribution. Placing a metallic nanolayer at the location of an asymmetric nodal plane results in the rejection of obliquely incident light and rendering the sheet-isolator omnidirectional [12].

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REFERENCES:

[1] Chang, K., “Handbook of microwave and optical components”. New York: J. Wiley, (1989).
[2] Dötsch, H., Bahllmann, N., Zhuromskyy, O., Hammer, M., Wilkens, L., Gerhardt, R., Hertel, P. and Popkov, A.F., “Applications of magneto-optical waveguides in integrated optics”. JOSA B, 22(1), pp.240-253, (2005).
[3] Shoji, Y., Ito, M., Shirato, Y. and Mizumoto, T., “MZI optical isolator with Si-wire waveguides by surface-activated direct bonding”. Optics express, 20 (16), pp.18440-18448, (2012).
[4] Kumar, P. and Levy, M., “On-chip optical isolation via unidirectional Bloch oscillations in a waveguide array”. Optics letters, 37(18), pp.3762-3764, (2012).
[5] Van Parys, W., Moeyersoon, B., Van Thourhout, D., Baets, R., Vanwolleghem, M., Dagens, B., Decobert, J., Le Gouezigou, O., Make, D., Vanheertum, R. and Lagae, L., “Transverse
magnetic mode nonreciprocal propagation in an amplifying AlGaInAsInP optical waveguide isolator”. *Applied physics letters*, 88(7), p.071115, (2006).

[6] Wang, Z., Chong, Y., Joannopoulos, J.D. and Soljačić, M., “Observation of unidirectional backscattering-immune topological electromagnetic states”. *Nature*, 461(7265), p.772, (2009).

[7] Wang, Z. and Fan, S., “Optical circulators in two-dimensional magneto-optical photonic crystals”. *Optics letters*, 30(15), pp.1989-1991, (2005).

[8] Bi, L., Hu, J., Jiang, P., Kim, D.H., Dionne, G.F., Kimerling, L.C. and Ross, C.A., “On-chip optical isolation in monolithically integrated non-reciprocal optical resonators”. *Nature Photonics*, 5(12), p.758, (2011).

[9] Saleh, B., & Teich, M., “Fundamentals of photonics (2nd ed.)”. *Hoboken, N.J: Wiley-Interscience*, (2007).

[10] Yu, X.J., Kwok, H.S., “Optical wire-grid polarizers at oblique angles of incidence”. *Journal of applied physics*, 93(8), pp.4407-4412, (2003).

[11] Grande, M., Bianco, G.V., Vincenti, M.A., de Ceglia, D., Capezzuto, P., Scalora, M., D’Orazio, A. and Bruno, G., “Optically transparent microwave polarizer based on quasi-metallic graphene”. *Scientific reports*, 5, p.17083, (2015).

[12] Chabanov A., Smith K., Carroll T., and Vitebskiy I., “Metal-dielectric photonic structures with extreme directionality: A concept of wide-aperture omnidirectional isolator,” in *2014 8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics*, (Institute of Electrical and Electronics Engineers, New York, 2014), pp. 79-81.

[13] Hägglund C., Apell S. P., and Kasemo B., “Maximized Optical Absorption in Ultrathin Films and Its Application to Plasmon-Based Two-Dimensional Photovoltaics” *Nano Letters*, 10 (8), 3135-3141 (2010).

[14] Zhang J., Macdonald K., Zheludev N., and Zhang J., “Controlling light-with-light without nonlinearity”. *Light: Science and Applications*, 1 (7), e18–e18 (2012).

[15] Huang, S., Xie, Z., Chen, W., Lei, J., Wang, F., Liu, K. and Li, L., “Metasurface with multi-sized structure for multi-band coherent perfect absorption”. *Optics express*, 26(6), pp.7066-7078, (2018).

[16] Salisbury W., “Absorbent Body of Electromagnetic Waves,” U. S. Patent 2,599,944, Jun 10 (1952).

[17] Fante R. L., and McCormack M.T., “Reflection Properties of the Salisbury Screen”, *IEEE Trans. on Antennas and Propagation*, 36 (10), 1443-1454 (1988).

[18] Wan, W., Chong, Y., Ge, L., Noh, H., Stone, A.D. and Cao, H., “Time-reversed lasing and interferometric control of absorption”. *Science*, 331(6019), pp.889-892, (2011).

[19] Chong, Y.D. and Stone, A.D., “Hidden black: Coherent enhancement of absorption in strongly scattering media”. *Physical review letters*, 107(16), p.163901, (2011).
[20] Chong, Y.D., Ge, L., Cao, H. and Stone, A.D., “Coherent perfect absorbers: time-reversed lasers”. *Physical review letters*, 105(5), p.053901, (2010).

[21] Baranov, D.G., Krasnok, A., Shegai, T., Alù, A. and Chong, Y., “Coherent perfect absorbers: linear control of light with light”. *Nature Reviews Materials*, 2(12), p.17064, (2017)

[22] Slater J.C., “Microwave Electronics” *D. Van Nostrand*, (1950).

[23] Yariv, A., “Universal relations for coupling of optical power between microresonators and dielectric waveguides”. *Electronics letters*, 36(4), pp.321-322, (2000).

[24] Yariv, A., “Critical coupling and its control in optical waveguide-ring resonator systems”. *IEEE Photonics Technology Letters*, 14(4), pp.483-485, (2002).

[25] Piper, J.R. and Fan, S., “Total absorption in a graphene monolayer in the optical regime by critical coupling with a photonic crystal guided resonance”. *Acids Photonics*, 1(4), pp.347-353, (2014).

[26] Liu, Y., Chadha, A., Zhao, D., Piper, J.R., Jia, Y., Shuai, Y., Menon, L., Yang, H., Ma, Z., Fan, S. and Xia, F., “Approaching total absorption at near infrared in a large area monolayer graphene by critical coupling”. *Applied Physics Letters*, 105(18), p.181105, (2014).

[27] Korolev, K.A., Subramanian, L. and Afsar, M.N., “Complex permittivity and permeability measurements of ferrite powders at millimeter waves”. In *Microwave Conference, 2005 European* (Vol. 2, pp. 3-pp). IEEE.

[28] Shalaby M., Peccianti M., Oizuk Y., Morandoti R., “A magnetic non-reciprocal isolator for broadband terahertz operation,” *Nature Communications*, 4, 1558 (2013).