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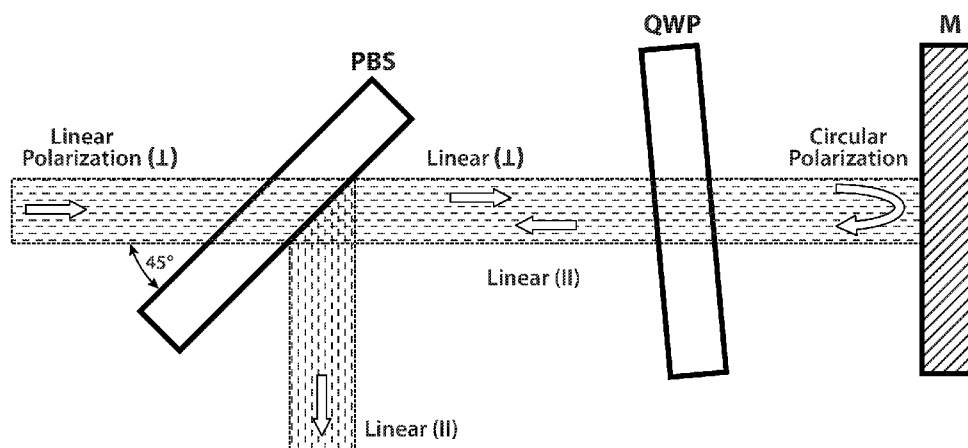


Figure 6

(57) **Abstract:** An isolator based on a waveguide-based artificial dielectric medium is scalable to a range of desired terahertz frequencies, has non-reciprocal transmission and provides low insertion loss and high isolation at various tunable terahertz frequencies, far exceeding the performance of other terahertz isolators, and rivaling that of commercial optical isolators based on the Faraday effect. This approach offers a promising new route for polarization control of free-space terahertz beams in various instrumentation applications. Artificial dielectrics are man-made media that mimic properties of naturally occurring dielectric media, or even manifest properties that cannot generally occur in nature. A simple and effective strategy implements a polarizing-beam-splitter and a quarter wave plate to form a highly effective isolator. Performance of the device is believed to exceed that of any other experimentally demonstrated method for isolation of back-reflections for terahertz beams.



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Artificial Dielectric Isolator for THz Radiation

This application is addressed to an isolator construction based on artificial dielectric materials for operation in the terahertz spectral regime. Applicants hereby incorporate by reference herein in its entirety the full text, drawings and disclosure of provisional application serial number 62/432,157 filed December 9, 2016 in the U.S. Patent and Trademark Office, as well as the full text, drawings and disclosure of provisional application serial number 62/470,685 filed March 13, 2017 in the U.S. Patent and Trademark Office, and also the full text, drawings and disclosure with its appendix of provisional application serial number 62/474,301 filed March 21, 2017 in the U.S. Patent and Trademark Office, which compactly describe a THz domain isolator construction and a series of measurements evaluating its operation with terahertz signals from a frequency-matched Polarizing Beam Splitter.

Government Support

This invention was made with government support under grant 1609521 awarded by the National Science Foundation. The government has certain rights in the invention.

Background and detailed description

A polarizing-beam-splitter (PBS) is a device that splits a linearly polarized beam into two orthogonal polarization components, in a pre-determined power ratio. In the THz region, there have been a few studies on PBSs using metamaterials [1], dielectric bi-layers [2], diffraction gratings [3], and recently, using form birefringence [4]. (numbers in square brackets refer to publications listed in the bibliography, *infra*. In all of these prior art cases, the fabrication of the device is complicated and not readily scalable. Here we present experimental characterization of a PBS involving a far simpler geometry and exhibiting remarkable performance. Our design is based on artificial dielectrics [5, 6], man-made media that mimic properties of naturally occurring dielectric media, or even manifest properties that cannot generally occur in nature. Although originally introduced by the microwave community, the wavelength scaling that result when shifting from microwaves to THz waves gives new life to this waveguide-based technology [7]. At the design frequency of 0.2 THz, our PBS exhibits an extinction ratio of

42 dB in transmission and 28 dB in reflection with an overall insertion loss of 0.18 dB, the best values ever reported in the THz range. Further, by combining our PBS with a quarter-wave-plate based on the same artificial-dielectric technology, we demonstrate a THz isolator with an isolation of 52 dB and an insertion loss less than one dB, at a frequency of 0.46 THz. This isolation is more than three orders of magnitude higher than recently demonstrated THz isolators based on graphene [8], and the insertion loss is considerably lower than previously demonstrated THz isolators based on ferrite materials [9, 10]. In addition, our design does not require an externally applied magnetic field. Indeed, the performance of our device rivals that of commercially available Faraday isolators at optical wavelengths. This simple method for achieving very high isolation will be invaluable for numerous applications involving high-power THz sources [11] or THz systems with highly sensitive receivers [12].

The isolator of the present invention will be described in connection with exemplary embodiments wherein a polarization beam splitter (PBS) provides polarization selectivity in the beam path, and a quarter wave plate (QWP) provides a phase delay, which in combination with the PBS, is used to reject reflections of the beam. The PBS operates with frequencies below cutoff, which depends upon the spacing of metal plates which constitute the artificial dielectric and the incident angle, while the QWP operates above a cutoff frequency that depends upon the plate spacing and introduces a phase delay which depends upon the plate width and the plate spacing. These two elements constructed with artificial dielectric materials result in superior operating characteristics.

Brief Description of the Drawings

The invention will be understood from the description and drawings herein, taken together with the claims appended hereto, wherein

Figure 1 shows a polarizing beam splitter (PBS) fabricated with artificial dielectric construction and simulations. Illustrated details include (a) Photograph of the PBS device with close-up views showing a square section of the stack-of-plates (looking on axis) and the bottom-corner of the mounting post. (b) Geometry of a single stainless-steel plate. (c, d) FEM simulations of the beam propagation at a frequency of 0.2 THz when the input electric field is linearly polarized (c) perpendicular, and (d) parallel, to the plates. The beam diameter is 1 cm and the angle of incidence is 45°. All dimensions are in millimeters.

Figure 2 schematically illustrates the experimental setup. The plane of the paper corresponds to the horizontal plane, which is also the plane of the plates. Gray areas represent the propagating beam. The complete detector sub-system (shown within the black dashed enclosure) can be moved intact, from the on-axis position to the 90° -off-axis position to measure either

5 transmission or reflection. All the polyethylene lenses are in confocal configurations to achieve maximum power transfer through the optical system. The inset diagram illustrates the general propagation behavior of the device (not drawn to scale and exaggerated for clarity) for an input beam with an arbitrary linear electric-field polarization direction and a broad spectrum having frequencies extending above and below the TE_1 -mode's cutoff.

Figure 3 shows transmission and reflection spectra. (a) Transmission spectra when the input polarization is parallel to the plates. The blue curve is the reference with no device, the green curve is with the device at normal incidence, and the red curve is with the device at 45° incidence. The device spectra correspond to TE_1 -mode propagation through the device. The sharp dips at 0.56 THz and 0.75 THz are due to water-vapor absorption. (b) Reflection spectra

10 when the input polarization is parallel to the plates. The red curve is with the device at 45° incidence and the blue curve is the reference with a polished aluminum mirror replacing the device. (c) Transmission spectra when the input polarization is perpendicular to the plates. The blue curve is the reference with no device and the red curve is with the device at 45° incidence. The device spectrum corresponds to TEM-mode propagation through the device. The insets in

15 (b) and (c) show the corresponding time-domain signals.

Figure 4 shows the power efficiency and extinction ratio. (a) Power efficiency for the transmission (blue dots) and reflection (red dots) arms, within the operational bandwidth. The blue solid curve gives the theoretical efficiency for the transmission arm taking into account only the ohmic loss. (b) Cross-polarization extinction ratio for the transmission (blue dots) and

20 reflection (red dots) arms, within the operational bandwidth.

Figure 5 is a schematic of the experimental setup used to investigate the Isolator. The isolator consists of the PBS combined with a QWP as shown by the red dashed enclosure in the upper right corner of the Figure. A photographic view of the isolator is shown inset. The input polarization is vertical and perpendicular to the plane of the paper. A gold mirror **M** was used to

25 create the back-reflection, and a silicon beam splitter **SBS** was used to tap it off to the receiver.

The PBS is at 45° incidence, by design, and the QWP is at a 12° incidence to eliminate the back-reflections originating from it.

Figure 6 is a schematic diagram of the isolator with the respective polarization directions given in operation (perpendicular to the plane of the paper or vertical, or parallel to the plane of the paper or horizontal).

Figure 7 shows measured isolation curves. Results are shown for two different quarter wave plates, QWP₁ (blue curve) and QWP₂ (red curve) designs, with close-up views of the peaks shown as insets.

Detailed description - Design and fabrication

The artificial dielectric medium as employed herein for splitting polarizations consists of a uniform stack of identical, rectangular metal plates. This stack-of-plates is electromagnetically equivalent to a stacked array of parallel-plate waveguides (PPWGs) [7], and in an exemplary embodiment are made of 30 μm thick stainless steel and are spaced 300 μm apart, as seen in the prototype device shown in Figure 1(a). The plates and the spacers are fabricated by chemical etching to avoid any strain or burring, which helps to maintain their flatness. The device is assembled by stacking the plates and spacers intermittently along two locating posts, such that the plates are free-standing, supported only by their ends. At each end, there is a square pad with a mounting hole as shown in Figure 1(b), which gives the actual shape of a plate. Once assembled, this stacked-plate arrangement results in a clear aperture of 20 mm. The magnified, close-up view of the 4 mm square section of the clear aperture illustrates the flatness of the plates and the uniformity of their spacing. Taking a slice across this image and using a graphical reconstruction method, we measure an average center-to-center plate spacing of 330 μm , with a standard deviation of 5 μm .

In the designed device geometry, the THz beam is directed at the stack-of-plates at an angle of 45° to the virtual surface emulated by the plate edges, with the plane of incidence parallel to the plate surfaces. The operation of the PBS relies on both the TEM and TE₁ fundamental modes of the PPWG [13, 14]. When the input electric-field is linearly polarized perpendicular to the plates, only TEM modes are excited in the PPWG array, and the beam propagates through the device without altering its path. This behavior is illustrated in the FEM simulation result shown in Figure 1(c), which plots the instantaneous electric field of the

propagating beam along the axial cross-section parallel to the plate surfaces, at a frequency of 0.2 THz. As long as the input beam diameter is sufficiently larger than the plate spacing (for proper mode-matching) and the interaction path-length is short, this TEM-mode propagation will be a very efficient (i.e., low loss) process [13]. On the other hand, when the input electric-field is linearly polarized parallel to the plates, only TE_1 modes can be excited in the PPWG array, and the propagation is governed by the mode's cutoff frequency. Input frequencies that are above the cutoff will propagate through the device, while those that are below the cutoff will be reflected. In fact, these below-cutoff frequencies will be *totally* and *specularly* reflected in a well-defined beam [7]. This behavior is illustrated in the FEM simulation result shown in Figure 1(d), which plots the instantaneous magnetic field of the propagating beam at a frequency of 0.2 THz.

For oblique incidence, the TE_1 -mode cutoff frequency is given by $c/(2b \cos \alpha)$, where c is the free-space velocity, b is the plate spacing, and α is the incidence angle [15]. For the demonstrated device, the cutoff is at 0.7 THz when the device is illuminated at 45° . Now, if the input electric-field is linearly polarized at an arbitrary angle (between 0° and 90°) to the plates, both the TEM and TE_1 modes are excited simultaneously. Then, the portion of the input beam (the perpendicular component) propagating via the TEM mode exits the device on axis, polarized perpendicular to the plates. This TEM-mode contribution is independent of the frequency. In contrast, the portion that could excite the TE_1 mode (the parallel component), if below cutoff, is totally reflected at 90° to the input axis, polarized parallel to the plates. By varying the angle of the input polarization, one can control the power division into the two output arms, thereby realizing a versatile PBS. Incidentally, if there is any parallel component at a frequency above the cutoff, this portion would propagate through the device via the TE_1 mode and exit the device with a slight lateral shift, polarized parallel to the plates. This general behavior of the device for an incident beam with an arbitrary linear polarization direction having frequencies extending below and above the cutoff is schematically illustrated in the inset of Figure 2. Since the PBS operation would be hampered by any excitation of the TE_1 mode, the upper limit of the operational bandwidth of the PBS is set by the mode's cutoff frequency. Therefore, it follows that the bandwidth can be increased by decreasing the plate spacing and/or increasing the incidence angle.

Experimental characterization - PBS

A prototype PBS device was experimentally investigated in transmission and reflection configurations using a THz time-domain spectroscopy system, as schematically depicted in Figure 2. In this spectroscopy system, both the transmitter and receiver modules are fiber coupled to the main controller unit, so as to accommodate the multiple polarization axes and spatial configurations. Throughout the experiment, the device was located between two wire-grid polarizers to purify the input and detected linear polarizations. Via external optics, the input beam was formed to a frequency-independent $1/e$ Gaussian diameter of approximately 10 mm and fairly well collimated. The same optical arrangement was employed for the output beam to maintain input-output symmetry. While the input optics were fixed in space, the detector sub-system could be moved (intact) from the on-axis position to the 90° -off-axis position to change from a transmission configuration to a reflection configuration. A 16 mm diameter aperture was situated in close proximity to the input transverse-plane of the device. This eliminated any energy “spill-over”, providing a true reference signal when the device was not in the beam path, and also served as a marker for the beam axis. In addition to three-axis linear translation, the device mount also included a precision rotation stage to adjust the incidence angle in the horizontal plane, along with precision control of the tilt in two perpendicular vertical planes, allowing complete three-axis rotational positioning.

Figure 3 illustrates various measured amplitude spectra that were obtained by Fourier transforming the detected time-domain signals. Figure 3(a) shows spectra corresponding to the purely TE_1 -mode behavior of the device in transmission. During this measurement, both the transmitter and receiver polarization axes (along with the input and output polarizer axes) were kept horizontal. Here, the blue curve corresponds to the reference signal when there is no device in the path of the beam. The sharp dips seen at 0.56 THz and 0.75 THz are due to water vapor absorption. The green curve corresponds to the signal when the device is in the path of the beam at normal incidence. This spectrum indicates a cutoff near 0.5 THz, which is expected for a 300 μm plate spacing. The red curve corresponds to the signal when the device is at 45° incidence (the designed operating configuration), and as predicted by theory, the cutoff shifts to a value near 0.7 THz. This TE_1 -mode diagnostic measurement is indicative of the quality of the device and serves as a demonstration of the operational bandwidth of the PBS.

For the spectra in Figure 3(b), the polarization axes of the transmitter, receiver, and the polarizers were maintained horizontal as before, but the detector sub-system was moved to

measure the reflected signal. The red curve corresponds to the reflected signal when the device is at 45° incidence. The blue curve corresponds to the reference signal when the device is replaced by a polished aluminum mirror. The inset gives the detected time-domain signals, and along with the spectra, they prove the highly efficient and non-dispersive broad-band operation of the device in reflection. The high-frequency attenuation of the device spectrum which appears to build up starting close to 0.7 THz is consistent with the TE_1 -mode transmission spectrum in Figure 3(a). Since this attenuation manifests for relatively low amplitude levels of the input spectrum (as evident by the reference), there is only minimal change in the reflected temporal signal.

For the spectra in Figure 3(c), the measurement configuration was changed back to transmission, and the polarization axes of the transmitter, receiver, and the polarizers, were rotated to be vertical. Therefore, this configuration investigates the purely TEM-mode behavior of the device. The blue curve corresponds to the reference signal when there is no device in the beam path. The red curve corresponds to the signal when the device is at 45° incidence to the input beam. The detected time-domain signals are given in the inset, and as before, along with the amplitude spectra, prove the highly efficient and non-dispersive broad-band operation of the device in transmission. This observation is not surprising since the TEM mode of the PPWG is a very low-loss and dispersion-less propagating mode [13]. However, it should be noted that in order to obtain this efficient propagation it was important for the beam axis to be aligned so as to be parallel to the plate surfaces with high accuracy, and also for the input polarization direction to be exceptionally well perpendicular to the plate surfaces. Deviations from these two conditions would result in additional losses, as the oblique incidence results in a longer interaction path-length, compared to that with normal incidence. It is not only the added ohmic loss that comes into play, but also the relative parallelism of the stack of plates.

Using the spectra in Figures 3(b) and (c), one can deduce the power efficiency of the device for the transmission and reflection arms. These efficiency curves are plotted in Figure 4(a) by the blue dots and red dots for transmission and reflection, respectively, within the operational bandwidth of the PBS. For the reflection arm, the efficiency curve is relatively flat throughout the bandwidth, and indicates a power efficiency of 96% at both 0.2 THz and 0.5 THz, for example. This corresponds to an insertion loss of only 0.18 dB. For the transmission arm, the efficiency is 96% at 0.2 THz, and drops to 84% at 0.5 THz. This corresponds to an insertion loss of 0.76 dB. For comparison, also plotted is the theoretical transmission (blue solid curve) taking

into account only the ohmic loss associated with TEM-mode propagation. The discrepancy with the experimental curve (especially as the frequency increases) implies that there are other sources of loss. Part of this extra loss is caused by the non-negligible impedance mismatch at the input and output surfaces of the device, even in the case of TEM-mode propagation [16]. This gives rise to two small reflections from these surfaces, which may also be affected by the finite thickness of the plates. In fact, these reflections played a role in the subsequent measurements that were carried out to estimate the cross-polarization extinction ratios of the PBS.

In the next measurement, the input polarization was oriented at 45° to the horizontal plate surfaces, and both the vertical and horizontal components of the output were measured, for both the transmission and reflection configurations separately. Therefore, for the transmission arm, in addition to the major component of the output that is polarized perpendicular to the plates, this also measures the minor component that is polarized parallel to the plates. This minor cross-polarization component is a result of energy leakage due to subtle device imperfections. The squared ratio of these two components gives the extinction ratio, which is plotted by the blue dots in Figure 4(b). This curve indicates extinction ratios of 42 dB and 39 dB at 0.2 THz and 0.5 THz, respectively. Similarly, for the reflection arm, in addition to the major component polarized parallel to the plates, this measures the minor component polarized perpendicular to the plates. In this case, the cross-polarization component is due to the two TEM-mode reflections at the input and output surfaces, as discussed above. The estimated extinction ratio is plotted by the red dots in Figure 4(b), where the observed ripple is due to the associated Fabry-Perot effect. This curve indicates extinction ratios of 28 dB and 22 dB at 0.2 THz and 0.5 THz, respectively. These values are not as impressive as for the transmission arm; however, a simple way to improve this extinction would be to add a polarizer to the reflection arm. This polarizer could be an identical artificial-dielectric device as used for the PBS, and would be extremely efficient since the beam would now be at normal incidence.

Experimental characterization - Isolator

We constructed an isolator for the THz region using a metal plate artificial dielectric construction, and the isolator performance characteristics were then measured. In optics, the primary purpose of an isolator is to minimize or eliminate feedback (back-reflections), while transmitting sufficient power in the forward direction. Isolators are essential for the stable and

reliable operation of lasers, especially high-power ones, in well-aligned complex optical systems, where back-reflections are inevitable. High-contrast isolators are also critical components in full-duplex communication systems [17]. In the THz region, there have been a few experimental studies on isolators, for example, using ferrite materials [see: D. H. Martin and R. J. Wylde, "Wideband circulators for use at frequencies above 100 GHz to beyond 350 GHz," IEEE Trans. Microwave Theory Tech. **57**, 99 (2009); and M. Shalaby, M. Peccianti, Y. Ozturk, and R. Morandotti, "A magnetic non-reciprocal isolator for broadband terahertz operation," Nature Commun. **4**, 1558 (2013)] or using graphene [M. Tamagnone, C. Moldovan, J. -M. Pouirol, A. B. Kuzmenko, A. M. Ionescu, J. R. Mosig, and J. Perruisseau-Carrier, "Near optimal graphene terahertz non-reciprocal isolator," Nature Commun. **7**, 11216 (2016).]. Our THz isolator is designed by combining a polarizing beam splitter (PBS) with a quarter-wave plate (QWP) that is also fabricated utilizing the same artificial-dielectric technology. This isolator design is shown schematically by the dashed-line enclosure in the upper right corner of the schematic diagram given in Figure 5, and this experimental configuration was used to investigate the isolator behavior. A detailed schematic diagram of the isolator with the respective polarization directions is given in Figure 6. Here, $\perp$ denotes perpendicular to the plane of the paper (or vertical) and $\parallel$ denotes parallel to the plane of the paper (or horizontal).

The QWP was fabricated using the same 30 μm thick stainless-steel plates as shown, for example in PCT/US17/65524 (claiming priority to 62/432,157 Filed 12/9/2016) which describes a Polarizing beam splitter for THz radiation, but with a plate spacing of 1 mm in a first design (denoted QWP₁), and a spacing of 0.8 mm in second design (denoted QWP₂). For the proper operation of the QWP, the plane of the plates is oriented at 45° to the input vertical polarization set by the PBS. Then, half of the input energy will propagate via the TEM mode and the other half via the TE₁ mode. After propagating through the device at different velocities, these two orthogonal polarization components will acquire a relative phase of 90° at a certain frequency. It can be shown that this occurs at a frequency given by $0.5cd[(1/b)^2 + (0.5/d)^2]$, where d is the propagation-path length. Accordingly, since $d = 2$ mm, this should occur at 0.32 THz and 0.49 THz for QWP₁ and QWP₂, respectively. Now, when there is a back-reflection, due to the "double-pass" through the QWP, the phase difference will become 180°. This will effectively rotate the polarization axis of the resultant reflected beam by 90° [18], rendering it horizontal,

and be diverted in the off-axis direction by the PBS, essentially isolating it from the input-beam path.

As shown in Figure 6, a gold mirror **M** was used to create the back reflection, and it was detected by tapping it off using a silicon beam splitter, *with* and *without* the isolator in place. The ratio of these two spectra, after converting to decibels, gives the isolation curves, as plotted in Figure 7. The QWP was mounted with an azimuthal tilt of 12° to eliminate the back-reflections generated at its surfaces. (This tilt is seen in both the schematic and the photo shown inset in Figure 6.) For the QWP₁ design, the maximum isolation is 48 dB, and this occurs at 0.32 THz, exactly as the theory predicts. For the QWP₂ design, the maximum isolation is 52 dB, and this occurs at 0.46 THz, slightly shifted from the theoretical value. This discrepancy may be due to a weaker tightening of the plates assembly, resulting in a slightly larger than expected plate separation. For completeness, the forward power transmission of the isolator was also measured in a different transmission configuration, and it was 85% and 80% (equivalent to an insertion loss of 0.71 dB and 0.97 dB) for the QWP₁ and QWP₂ designs, respectively, at the peak isolation frequencies. A suitable arrangement that may provide continuous control of the plate spacing would allow dynamic tunability of the isolation-peak, adding versatility to the isolator.

Discussion

In conclusion, we have experimentally demonstrated a highly efficient and versatile PBS for the THz spectral regime based on artificial dielectrics. The device geometry is exceedingly simple compared to all previous PBS attempts for this spectral region. Furthermore, the PBS exhibits insertion losses as low as 0.18 dB and cross-polarization extinction ratios as high as 42 dB. By combining this PBS with a QWP of the same artificial-dielectric technology, we also demonstrate a THz isolator with peak isolations as high as 52 dB. This work opens up a whole new generation of highly effective, highly efficient, easy to fabricate, and inexpensive artificial-dielectric polarimetric devices for the THz region. Furthermore, since the devices are made from stacked metallic plates, as opposed to conventional dielectric materials, they will also uniquely possess extremely high power handling capabilities, limited only by the breakdown of air within the plates.

Bibliography

- [1] X. G. Peralta, E. I. Smirnova, A. K. Azad, H. T. Chen, A. J. Taylor, I. Brener, and J. F. O'Hara, "Metamaterials for THz polarimetric devices," *Opt. Exp.* **17**, 773 (2009).
- [2] J. Li, D. Xu, and J. Yao, "Compact terahertz wave polarizing beam splitter," *Appl. Opt.* **49**, 4494 (2010).
- [3] C. W. Berry and M. Jarrahi, "Broadband terahertz polarizing beam splitter on a polymer substrate," *J. Infrared Milli. Terahz. Waves* **33**, 127 (2012).
- [4] A. I. Hernandez-Serrano and E. Castro-Camus, "Quasi-Wollaston-prism for terahertz frequencies fabricated by 3D printing," *J. Infrared Milli. Terahz. Waves* (2017).
doi:10.1007/s10762-016-0350-1.
- [5] W. E. Kock, "Metal-lens antennas," *Proc. IRE.* **34**, 828 (1946).
- [6] S. S. D. Jones and J. Brown, "Metallic Delay Lenses," *Nature* **163**, 324 (1949).
- [7] R. Mendis, M. Nagai, Y. Wang, N. Karl, and D. M. Mittleman, "Terahertz artificial dielectric lens," *Scient. Rep.* **6**, 23023 (2016).
- [8] M. Tamagnone, C. Moldovan, J. -M. Pouirol, A. B. Kuzmenko, A. M. Ionescu, J. R. Mosig, and J. Perruisseau-Carrier, "Near optimal graphene terahertz non-reciprocal isolator," *Nature Commun.* **7**, 11216 (2016).
- [9] D. H. Martin and R. J. Wylde, "Wideband circulators for use at frequencies above 100 GHz to beyond 350 GHz," *IEEE Trans. Microwave Theory Tech.* **57**, 99 (2009).
- [10] M. Shalaby, M. Peccianti, Y. Ozturk, and R. Morandotti, "A magnetic non-reciprocal isolator for broadband terahertz operation," *Nature Commun.* **4**, 1558 (2013).
- [11] S. Takahashi, G. Ramian, M. S. Sherwin, L. C. Brunel, and J. V. Tol, "*Submegahertz linewidth at 240 GHz from an injection-locked free-electron laser*," *Appl. Phys. Lett.* **91**, 174102 (2007).
- [12] M. Paquay, J. Marti-Canales, L. Rolo, G. Forma, D. Dubruel, R. Wylde, B. Maffei, D. Doyle, G. Crone, J. Tauber, and R. Hills, "Alignment verification of the PLANCK reflector configuration by RCS measurements at 320 GHz," *Proc. of the 38th European Microwave Conference*, 765 (2008).
- [13] R. Mendis and D. Grischkowsky, "Undistorted guided-wave propagation of subpicosecond terahertz pulses," *Opt. Lett.* **26**, 846 (2001).
- [14] R. Mendis and D. M. Mittleman, "Comparison of the lowest-order transverse-electric (TE₁)

and transverse-magnetic (TEM) modes of the parallel-plate waveguide for terahertz pulse applications,” *Opt. Exp.* **17**, 14839 (2009).

[15] R. Mendis and D. M. Mittleman, “A 2-D artificial dielectric with $0 \leq n < 1$ for the terahertz region,” *IEEE Trans. Microw. Theory Tech.* **58**, 1993 (2010).

5 [16] M. Mbonye, R. Mendis, and D. M. Mittleman, “Study of the impedance mismatch at the output end of a THz parallel-plate waveguide,” *Appl. Phys. Lett.* **100**, 111120 (2012).

[17] N. Reiskarimian and H. Krishnaswamy, “Magnetic-free non-reciprocity based on staggered commutation,” *Nature Commun.* **7**, 11217 (2016).

[18] E. Hecht, *Optics*, Addison Wesley, San Francisco, 2002.

CLAIMS

1. An isolator fabricated using waveguide-based artificial dielectric formed with thin metal plates and configured for use in THz frequency systems to eliminate harmful back-reflections.

2. An isolator according to claim 1, constructed by combining a polarizing beam splitter (PBS) formed with an artificial dielectric, and a quarter wave plate (QWP) also formed with an artificial dielectric, the PBS and QWP being oriented and positioned to block, divert or remove harmful or deleterious back reflections.

3. A quarter wave plate (QWP) fabricated with an artificial dielectric formed of thin spaced-apart metal plates, wherein the plates define orientation of a plane at 45° to an input vertical polarization of a process beam from a polarizing beam splitter (PBS), such that half of the input energy will propagate via the TEM mode and the other half via the TE_1 mode such that the two orthogonal polarization components acquire a one-pass relative phase of 90° at a certain frequency and a return pass relative phase of 180° upon passing back to effectively rotate the polarization axis of the reflected beam by 90° , rendering it horizontally polarized, so it is diverted in the off-axis direction by the PBS and essentially isolated from the input-beam path.

4. A THz device for a radar system, a send/receive full duplex communication system or some other high power application system that operates with THz-frequency signals, wherein the device includes a first array of spaced-apart conductive plates forming an artificial-dielectric polarizing beam splitter (PBS), and a second array of spaced-apart conductive plates forming an artificial-dielectric quarter wave plate (QWP) in the path of a beam from the first array, the second array being positioned and oriented to remove any reflections or back-scatter emanating from it.

5. A THz device or quarter wave plate (QWP) formed with an array of spaced apart metal plates, wherein the metal is stainless steel (or any highly conducting metal), the plates are flat and parallel, and optionally wherein the plates are spaced apart by active thickness piezoelectric pads or other actuator operable to tune the plate-spacing of the array for isolating a signal of defined THz frequency.

6. A device according to claim 3, wherein the metal plates are 30 μm thick stainless steel plates with a plate spacing of 1 mm in one design (QWP_1), or a spacing of 0.8 mm in another design (QWP_2) for terahertz signals comprising an array of spaced apart parallel and flat stainless
5 steel plates oriented in a plane arranged and positioned in relation to a polarizing beam splitter (PBS) to pass a beam of defined polarization state with low insertion loss, from an input device such as a THz laser or an amplifier or a transmitter/receiver, while isolating and protecting the input device from back reflection, thereby allowing operation with one or more of enhanced
10 signal quality, reliability, long term stability, long lifetime or low noise.

7. A device according to claim 3, wherein the plates of the QWP are dimensioned to define a propagation path length d and plate spacing b to produce a 90 degree phase shift at a THz frequency f given by $f = 0.5cd [(1/b)^2 + (0.5/d)^2]$ where c is the free space velocity.

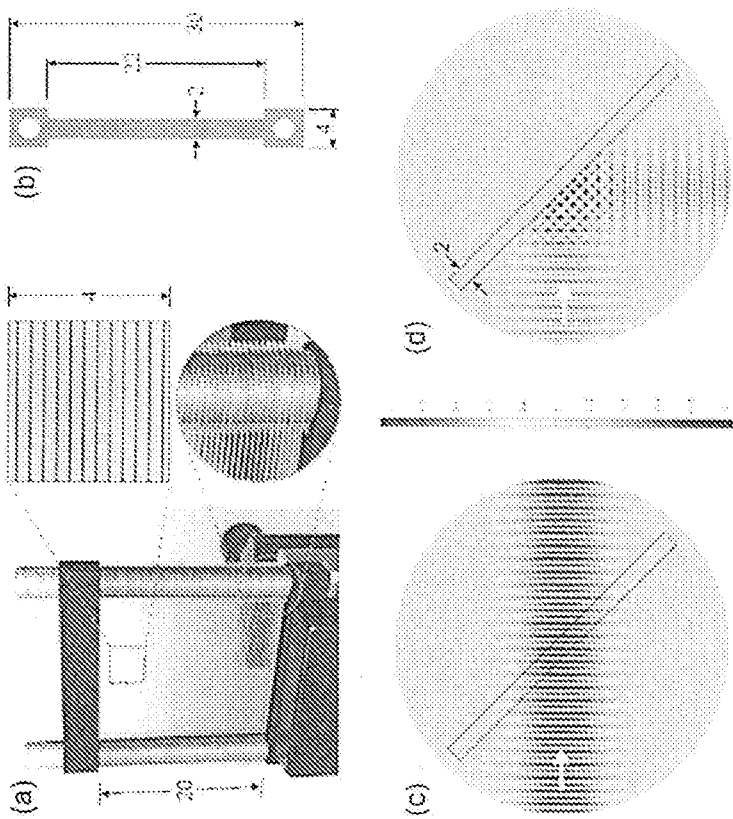


Figure 1

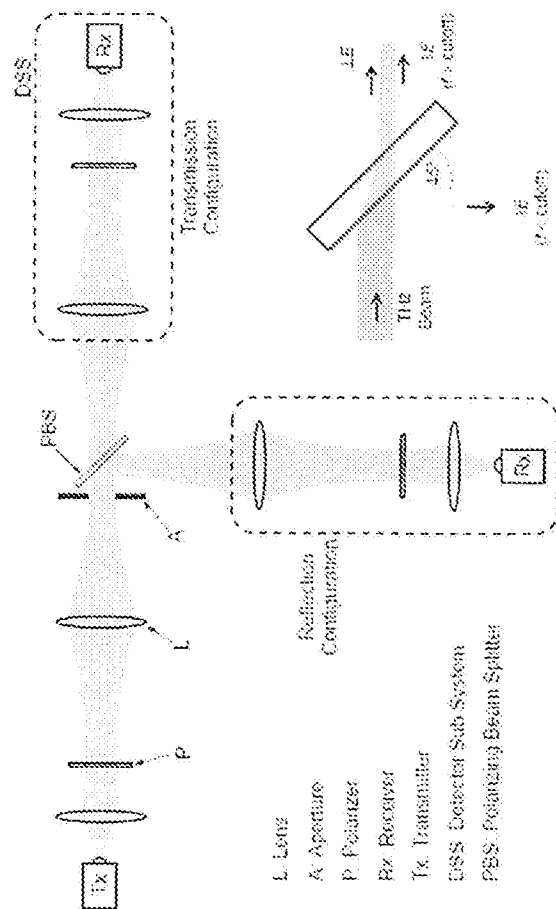


Figure 2

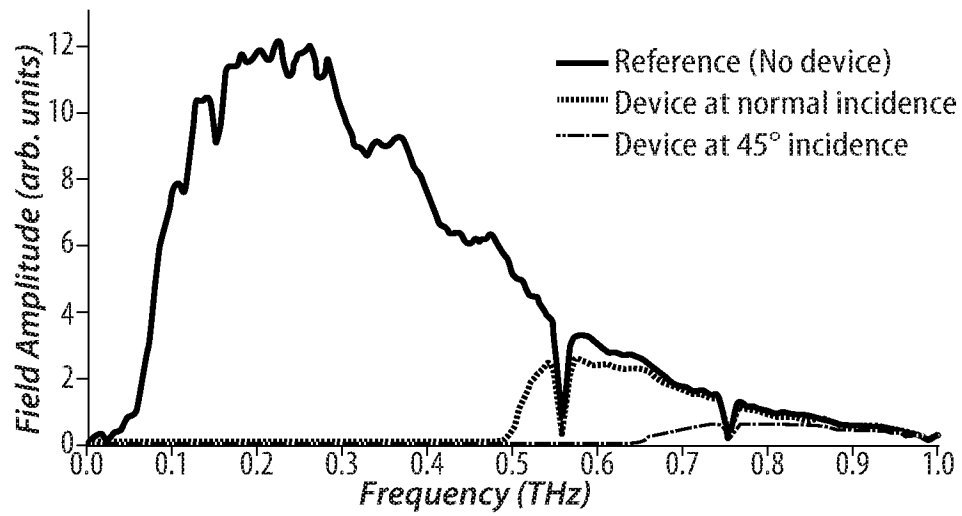


Figure 3a

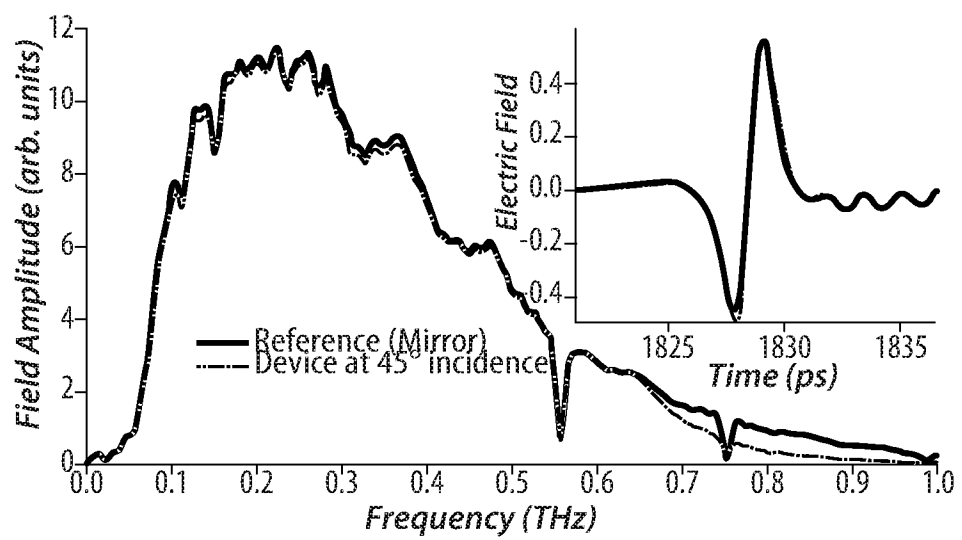


Figure 3b

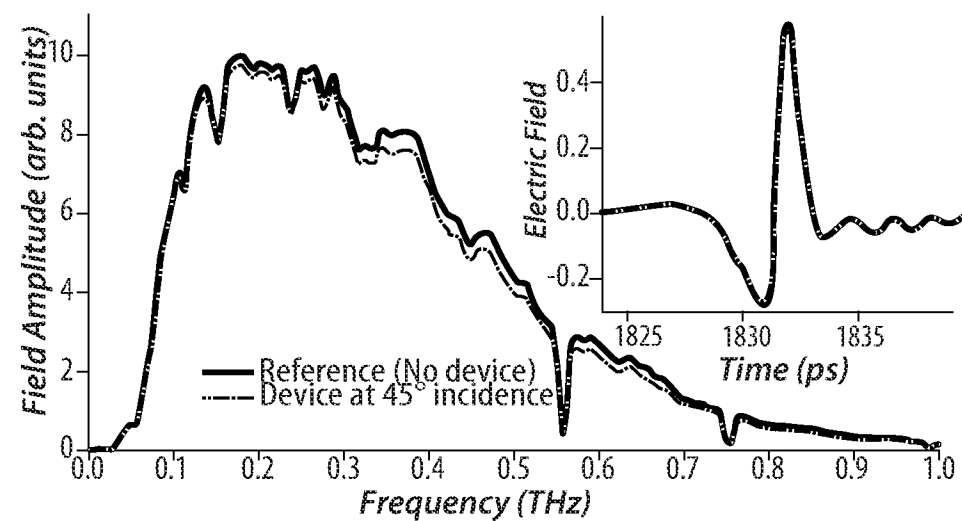


Figure 3c

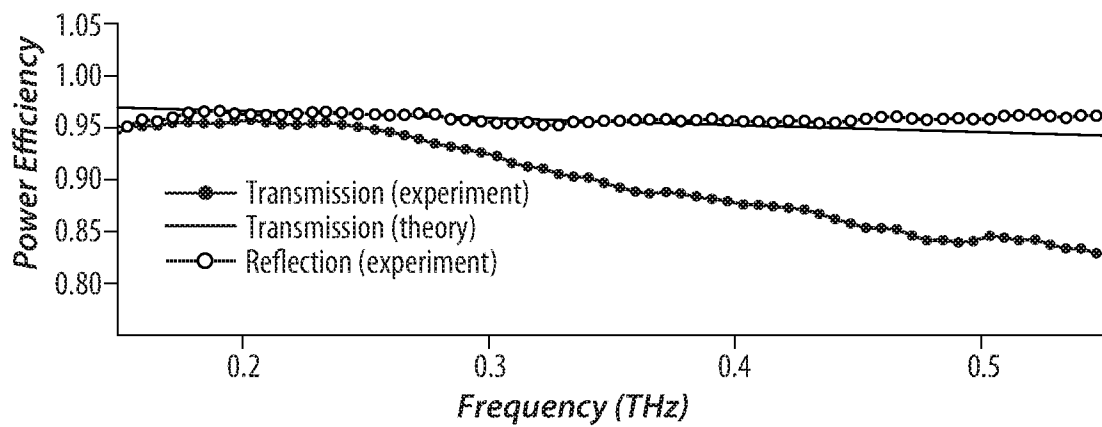


Figure 4a

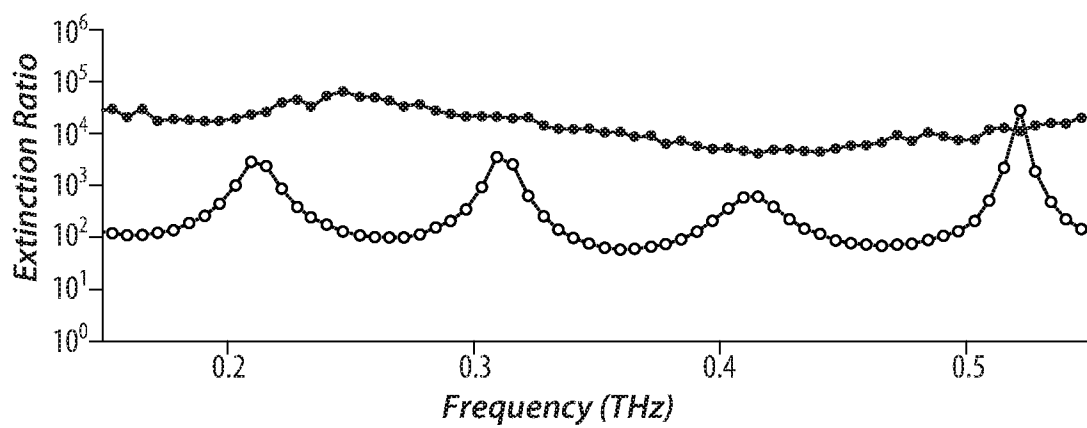


Figure 4b

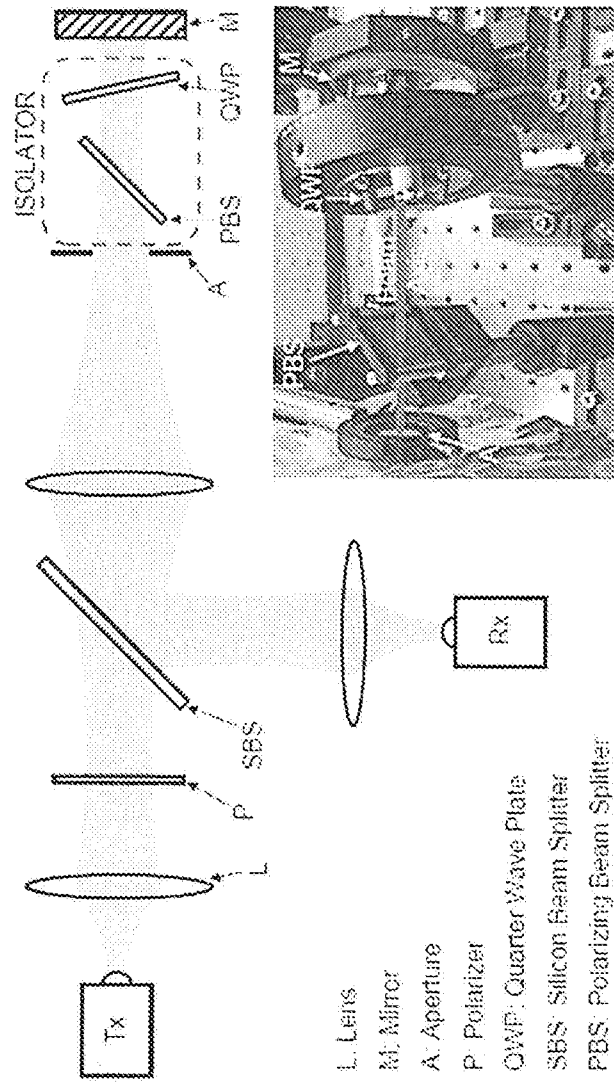


Figure 5

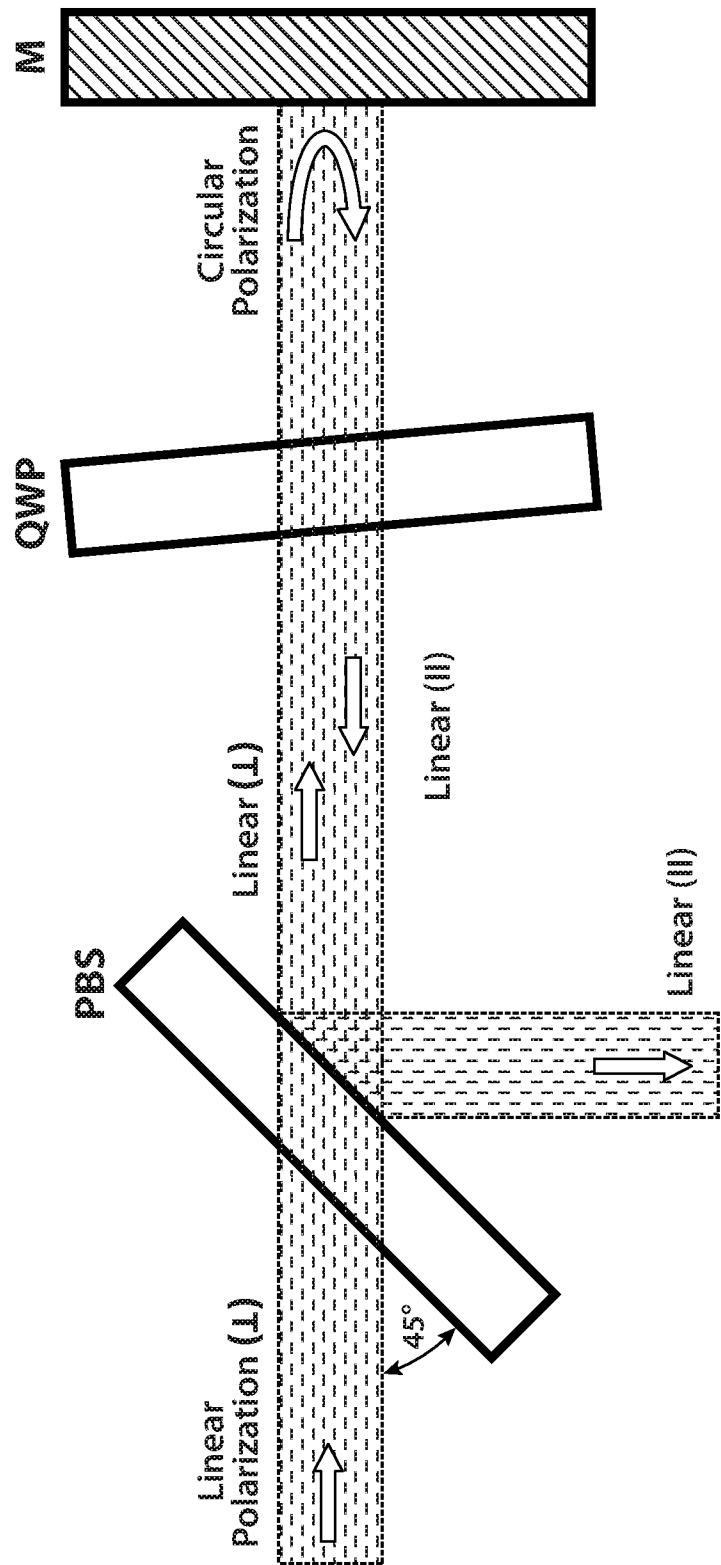


Figure 6

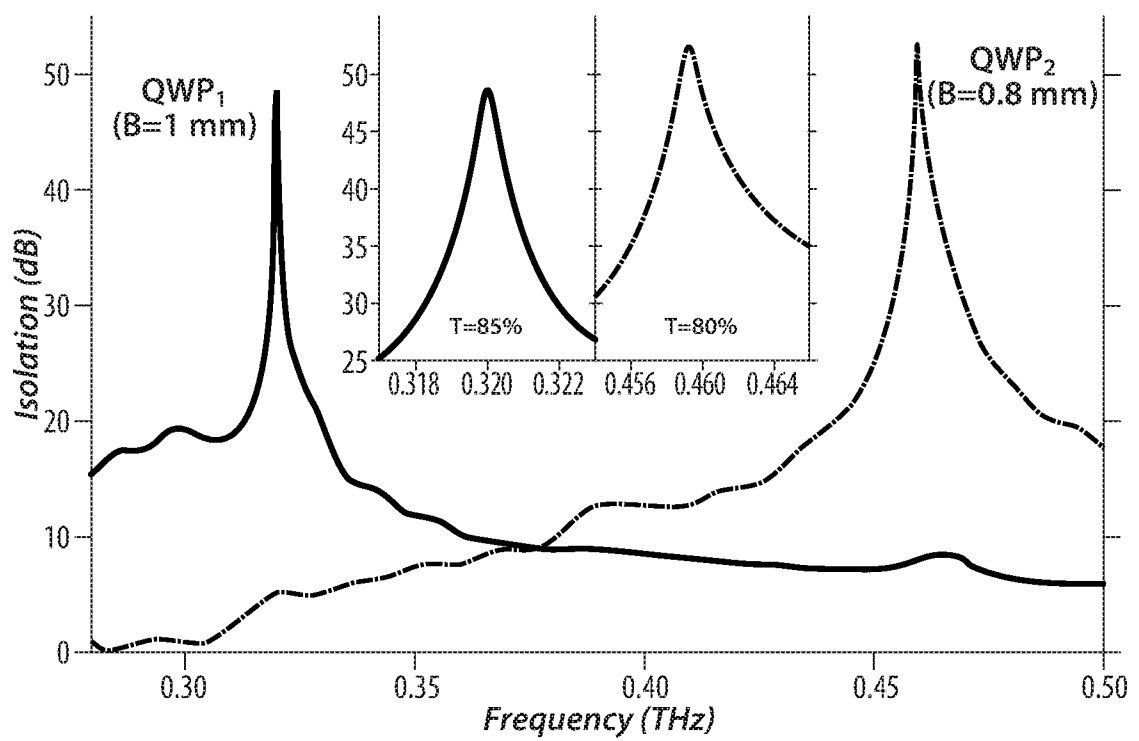


Figure 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2018/022158

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G02B 5/30; G02B 5/20 (2018.01)

CPC - G02B 5/3041; G02B 6/29325; G02B 6/29332 (2018.05)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 257/79; 333/21A; 333/35 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2006/0203324 A1 (HARRIS et al) 14 September 2006 (14.09.2006) entire document	1, 2, 4, 5
Y	US 2007/0296032 A1 (STUMBO et al) 27 December 2007 (27.12.2007) entire document	1-5, 7
Y	US 2002/0179912 A1 (BATCHKO et al) 05 December 2002 (05.12.2002) entire document	3, 7
Y	US 2013/0070326 A1 (FRISKEN et al) 21 March 2013 (21.03.2013) entire document	3, 7
A	US 2016/0077261 A1 (CALIFORNIA INSTITUTE OF TECHNOLOGY) 17 March 2016 (17.03.2016) entire document	1-7
A	US 2010/0142047 A1 (FUJII et al) 10 June 2010 (10.06.2010) entire document	1-7
A	US 2015/0116721 A1 (PRESIDENT AND FELLOWS OF HARVARD COLLEGE) 30 April 2015 (30.04.2015) entire document	1-7

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

08 May 2018

Date of mailing of the international search report

15 MAY 2018

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