A one-way mirror: High-performance terahertz optical isolator based on magneto-plasmonics

Shuai Lin,1 Sinhara Silva,2 Jiangfeng Zhou,2 and Diyar Talbayev1,*

1Department of Physics and Engineering Physics,
Tulane University, 6400 Freret St., New Orleans, LA 70118, USA
2Department of Physics, The University of South Florida,
Florida, Tampa, Florida, 33620-7100, USA
(Dated: May 1, 2018)

Abstract

We explore the magneto-optical properties of conduction electrons in InSb in Voigt geometry at oblique incidence angles. In parallel magnetic field, the oblique incidence reflectance exhibits high non-reciprocity, while the transmittance remains reciprocal. This phenomenology, combined with the unique magneto-plasmonic properties of InSb (high electron mobility, low effective mass, and temperature-tunable bulk plasma frequency), allows the design of a simple and high-performance THz optical isolator that works directly with linearly polarized light. We demonstrate that the isolation power of the device exceeds 35 dB with the insertion loss of only -6.2 dB. The simplicity of the isolator design is unmatched among the proposed THz isolator concepts to date.
I. INTRODUCTION

Terahertz (THz) science and technology has grown into a broad and interdisciplinary area with high impact on fundamental science and real-world applications. Actively applied THz research areas include security screening, THz imaging for quality control and medical diagnostics, sensing, and wireless communications, among others\textsuperscript{1–4}. As the photonic THz sources become increasingly powerful, THz optical isolators will play a crucial role in communications and other THz applications by allowing source protection and minimizing unwanted reflections that can degrade the system performance\textsuperscript{5,6}. In this article, we demonstrate a high-performance THz optical isolator with the simplest of designs that takes advantage of the non-reciprocal reflectance of magneto-plasma in the semiconductor InSb. The isolator achieves 35 dB of isolation performance with only -6.2 dB insertion loss.

An optical isolator is a passive non-reciprocal device that allows light propagation in one direction and prevents the back-reflected light from passing in the opposite direction. At visible and infrared wavelengths, an optical isolator typically relies on the Faraday effect and a pair of polarizers with relative 45° orientation to block the back-reflected beam from reaching a laser source. This architecture uses the Faraday rotation in non-absorbing media and breaks down at THz wavelengths, where one of the eigenpolarizations in the Faraday medium (either right-circular or left-circular) typically experiences a high loss. After the THz wave propagates through the medium, it acquires a high degree of ellipticity. Often, one of the eigenpolarizations is fully absorbed, and the remaining light is fully circularly polarized\textsuperscript{7}. As a result, there are no widely adopted solutions for THz optical isolators that work with linearly polarized inputs and outputs. Operation with linear polarization is the most desirable because many photonic THz emitters and receivers operate with linearly polarized light.

Faraday effect and magneto-optical Kerr effect can still be used in THz isolators if polarization-converting elements, such as waveplates, are included, even though they may add significant complexity and degrade the performance of the device. High-mobility semiconductors\textsuperscript{7–14}, graphene\textsuperscript{15–20}, ferrofluids\textsuperscript{21}, and magnetic materials\textsuperscript{22} have been explored as a suitable Faraday medium. The best known performance of this type of isolator was demonstrated by Tamagnone \textit{et al.}\textsuperscript{16} in a graphene-based device with the isolation of 18 dB and insertion loss of 7.5 dB in applied magnetic field of 7 T. The quoted performance is for
circular, not linear, polarization of input and output THz beams.

Another fundamental approach to THz optical isolation is based on nonreciprocal di-
rectional dichroism in magnetic materials that are also structurally chiral\textsuperscript{23} or polar\textsuperscript{24–27}. While the THz isolation performance of these materials can be very high\textsuperscript{27}, they typically operate at impractically low temperatures (\(\leq 100\) K) and high magnetic fields (\(\geq 7\) T). Alternatively, the non-reciprocal dispersion of surface magneto-plasmons in parallel magnetic field\textsuperscript{28,29} has been proposed as the fundamental basis for one-way THz waveguide-based devices\textsuperscript{30,31}. Other theoretical proposals have employed magneto-plasmonic metasurfaces and metamaterials to achieve THz isolation\textsuperscript{32–34}. These theoretical proposals have not been implemented and may be difficult and expensive for practical fabrication.

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{figure1.png}
\caption{Conceptual design of the proposed THz optical isolator. A slab of InSb is placed in parallel magnetic field directed along the cartesian \(y\) direction. The THz beam is incident obliquely in the \(x\)-\(z\) plane and is \(p\)-polarized, i.e., the THz electric field oscillates in the \(x\)-\(z\) plane. Beam 1 experiences high reflectance. Beam 2, which travels in the backward propagation direction relative to beam 1, experiences negligible reflectance and is absorbed by InSb.}
\end{figure}

We use the non-reciprocal reflection of magneto-plasmas to design and implement a simple, tunable, and high-performance THz isolator working with linearly polarized THz light in reflection geometry. Our isolator works at room temperature in very moderate magnetic field (\(\sim 0.2\) T). Therefore, it can serve as a practical alternative to Faraday-based and other
proposed THz isolation architectures. Even though the reflectance of magneto-plasma was investigated earlier by Remer et al., the potential applications of InSb to non-reciprocal THz devices has remained unexplored. Remer et al. ascribed the non-reciprocity of reflectance to a non-resonant coupling of the incident light to surface magneto-plasmons. We find that such coupling, which is forbidden by momentum conservation, is not necessary and the surface magneto-plasmons do not play a role in the observed non-reciprocity.

Figure 1 shows the fundamental design of the THz optical isolator. The enabling material is the semiconductor InSb that possesses a temperature-tunable charge carrier density and a high electron mobility. A magnetic field $B$ is applied parallel to the InSb surface along the cartesian $y$ direction, Fig. 1. THz light of the linear $p$-polarization (THz electric field in the $x$-$z$ plane) impinges obliquely in the $x$-$z$ plane on the InSb surface. In this geometry, the reflectance of the THz beam is non-reciprocal: the reflectance is high in the forward direction labeled 1 in Fig. 1. The reflectance in the backward direction (labeled 2) can be practically zero - the backward-traveling beam is absorbed by InSb, providing the necessary optical isolation.

In the geometry of Fig. 1 (magnetic field $B$ along the $y$ axis), the dielectric permittivity of InSb is described by the following tensor components:

$$\epsilon_{xx} = \epsilon_{zz} = \epsilon_\infty - \frac{\omega_p^2(\omega^2 + i\gamma\omega)}{(\omega^2 + i\gamma\omega)^2 - \omega^2\omega_c^2} + \epsilon_{ph},$$

$$\epsilon_{yy} = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} + \epsilon_{ph},$$

$$\epsilon_{xx} = -\epsilon_{zz} = \frac{i\omega_p^2\omega_c}{(\omega^2 + i\gamma\omega)^2 - \omega^2\omega_c^2},$$

$$\epsilon_{ph} = \epsilon_\infty(\frac{\omega_t^2 - \omega_l^2}{\omega_t^2 - \omega^2 - i\gamma_{ph}\omega}).$$

In Eqs. (1)-(3), $\omega_p = (ne^2/m^*\epsilon_0)$ is the plasma frequency determined by the carrier density $n$ and their effective mass $m^*$, $\gamma$ is the carrier scattering rate, $\epsilon_\infty = 15.6$ is the background high-frequency dielectric constant, and $\omega_c = \frac{eB}{m^*}$ is the electron cyclotron frequency set by the applied magnetic field $B$. The dielectric response of charge carriers is described in the Drude model. The phonon contribution to the dielectric function is described by Eq. (4), where $\omega_t$ and $\omega_l$ are the transverse and longitudinal optical phonon frequencies and $\gamma_{ph}$ is the phonon damping rate.
The transmitted and reflected THz amplitude at the air/InSb interface can be computed using Maxwell’s equations and the continuity conditions for the fields \( \vec{E} \) and \( \vec{D} \). The equations for the amplitude reflection coefficients \( r_p \) and \( r_s \) of the p- and s-polarized waves at the air/InSb interface take the form

\[
\begin{align*}
    r_p &= \frac{\varepsilon_{xx} \sin \alpha + \varepsilon_{xx}(\kappa + \varepsilon_v \cos \alpha)}{\varepsilon_{xx} \sin \alpha + \varepsilon_{xx}(\kappa - \varepsilon_v \cos \alpha)}, \\
    r_s &= \frac{\cos \alpha - \sqrt{\varepsilon_{yy} \cos \alpha'}}{\cos \alpha + \sqrt{\varepsilon_{yy} \cos \alpha'}},
\end{align*}
\]

where \( \alpha \) is the incidence angle (Fig. 1), \( \alpha' \) is the refracted angle inside InSb given by Snell’s law \( \sin \alpha = \sqrt{\varepsilon_{yy} \sin \alpha'} \), \( \varepsilon_v = \varepsilon_{xx} + \varepsilon_{xx}^2/\varepsilon_{xx} \), and \( \kappa = -(\varepsilon_v - \sin^2 \alpha)^{1/2} \). The refracted angle \( \alpha'_p \) in the p-polarization is different from \( \alpha'_s \) and is given by the wavevector \( \mathbf{k} = (\omega/c)(\sin \alpha, 0, \kappa) \). In Eq. (5), the positive incidence angle \( \alpha \) corresponds to the forward propagation direction labeled 1 in Fig. 1; the negative \( \alpha \) corresponds to the backward propagation direction labeled 2. Equation (5) shows that the complex reflection coefficient \( r_p \) is different for positive and negative angles \( \alpha \), which makes it different for the forward and backward directions 1 and 2. In the absence of any damping in our model, which corresponds to setting the rates \( \gamma \) and \( \gamma_{ph} \) to zero in Eqs. (1)-(4), Equation (5) has the form \( (iA \sin \alpha + B)/(iA \sin \alpha + C) \) with real quantities \( A \), \( B \), and \( C \). In this case, changing the propagation direction from 1 to 2 changes only the phase of \( r_p \) and not its amplitude. To achieve non-reciprocity of the amplitude of \( r_p \), damping must be present and is naturally introduced via the damping rates \( \gamma \) and \( \gamma_{ph} \). The absence of non-reciprocity in the intensity reflectance \( R = |r_p|^2 \) when \( \gamma = 0 \) has led Remer et al.\textsuperscript{35} to conclude that the propagating surface magneto-plasmons and their non-reciprocal dispersion are instrumental to achieve the non-reciprocity of \( R \). However, we find that any damping, for example introduced by \( \gamma_{ph} \), leads to non-reciprocal \( R \), which casts doubt on the role of propagating surface magneto-plasmons. This doubt is further reinforced when we consider that the coupling of the incident wave to the surface plasmons is forbidden by momentum conservation. According to Eq. (6), the reflectance in the s-polarization is perfectly reciprocal.

Equation (5) provides the fundamental basis for our THz isolator. For a complete comparison between the theory and our measurements, we also provide the expressions for the transmitted amplitude in p- and s-polarizations for an InSb wafer of thickness \( d \):

\[
t_p = e^{-i(\omega/c)nd}(1 + r_p)(1 - r_p)(a - b)\frac{1}{a(1 + r_p) - b(1 - r_p)},
\]

(7)
TABLE I: Drude parameters \((\omega_p, \gamma)\) of InSb and magnetic field \(B\) determined from simultaneous fitting of reflection and transmission data at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>(\omega_p/2\pi) (THz)</th>
<th>(\gamma) (THz)</th>
<th>(B) (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.35 ± 0.05</td>
<td>1.05 ± 0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>220</td>
<td>0.8 ± 0.02</td>
<td>1.19 ± 0.03</td>
<td>0.18</td>
</tr>
<tr>
<td>260</td>
<td>1.45 ± 0.02</td>
<td>1.5 ± 0.05</td>
<td>0.165</td>
</tr>
<tr>
<td>295</td>
<td>2.11 ± 0.03</td>
<td>1.65 ± 0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[
t_s = \frac{4\sqrt{\varepsilon_{yy}} \cos \alpha \cos \alpha'_{s}}{(\cos \alpha + \sqrt{\varepsilon_{yy}} \cos \alpha'_{s})^2} \exp \left( -i\sqrt{\varepsilon_{yy}} \omega d \frac{c}{\cos \alpha'_{s}} \right),
\]

where

\[
a = \frac{\epsilon_{xz} \sin \alpha - \epsilon_{xx} \kappa}{\epsilon_{xz} \sin \alpha + \epsilon_{xx} \kappa},
\]

\[
b = -e^{-2i(\omega/c)\kappa d} \frac{\epsilon_{xz} \sin \alpha + \epsilon_{xx} \kappa + \epsilon_{xx} \epsilon_{xx} \cos \alpha}{\epsilon_{xz} \sin \alpha - \epsilon_{xx} \kappa + \epsilon_{xx} \epsilon_{xx} \cos \alpha}.
\]

The transmitted amplitudes were computed by omitting the Fabry-Perot reflections within the InSb wafer. These reflections add a negligible contribution to either reflectance or transmittance of a thick wafer (\(\sim 0.5\) mm) because our THz isolator works near the bulk plasma frequency were the absorption is high.

In the next section, we describe experimental tests of the proposed THz optical isolator and discuss the optimization of its performance.

II. RESULTS AND DISCUSSION

We used a commercial nominally undoped InSb wafer of 0.5 mm thickness. The temperature-independent parameters of the optical-phonon part of the dielectric function, Eq. (4), were determined from the normal-incidence transmission spectra at 260 K, 220 K, and 180 K to be \(\omega_t/2\pi=5.90\) THz, \(\omega_l/2\pi=5.54\) THz, and \(\gamma_{ph} = 3.77\) THz for all temperatures\(^7,38\). The temperature-dependent Drude model parameters \(\omega_p\) and \(\gamma\) were determined by fitting all available reflection and transmission spectra at the same time and are listed in Table I. The values of magnetic field applied in the Voigt geometry, Fig. 1, were measured to be 0.20 T and 0.42 T at room temperature.

Figure 2(a) shows the amplitude reflectance of a \(p\)-polarized THz beam incident at 45°
FIG. 2: (a) The measured (circles) and calculated (solid lines) amplitude reflectance of InSb with and without external magnetic field in the Voigt geometry, Fig. 1. The incident THz beam is \( p \)-polarized. The reflectance exhibits a significant difference between positive and negative magnetic fields, which is equivalent to non-reciprocity of reflection. (b) Amplitude reflectance in the \( p \) polarization normalized by reflectance in the \( s \) polarization for positive and negative magnetic field. The \( s \)-polarized reflectance does not depend on the direction of magnetic field and does not exhibit the non-reciprocity.

on InSb at 220 K and in magnetic field \( B = 0 \) T and \( B = \pm 0.18 \) T. The reflected amplitude at 220 K is normalized by the amplitude at 295 K for all fields \( B \). The zero-field reflectance displays the expected plasma edge at 0.8 THz plasma frequency, which is a temperature-tunable value (Table I). In the applied magnetic field \( B = 0.18 \) T, the plasma edge splits into two minima whose separation depends on the applied magnetic field. The solid lines in Fig. 2(a) represent the fitting of the measured data to Eq. (5). The magnetic field strength was used as a fitting parameter and found to be \( B = 0.18 \) T, which is slightly lower than the
measured room-temperature value of 0.20 T. We find that at all measurement temperatures, the magnetic field determined from the fitting of optical spectra is slightly lower than the measured field (Table I). We attribute this discrepancy to the nonuniformity of the magnetic field created by the permanent magnets and to the possible difference between the positioning of the Gaussmeter probe and of the THz beam on the InSb wafer. In addition, the size of the Gaussmeter probe is likely 5-10 times smaller than the size of the focused THz beam, which can also result in the lower apparent field strength in the optical measurements. We also find that the magnetic field value determined from the fitting of optical data depends on temperature. Such behavior is expected as the magnetization of the permanent magnet can increase as the temperature is lowered (Table I). Most importantly, the depth of each reflectance minimum depends on the direction of applied magnetic field. According to Eq. (5), the change in direction of magnetic field is equivalent to changing the direction of incidence of the THz beam from positive angle $\alpha$ to negative $-\alpha$ at constant magnetic field. This is because the off-diagonal tensor component $\epsilon_{xz}$ changes sign upon reversal of magnetic field. The reflectance data of Fig. 2(a) demonstrate the non-reciprocal reflectance of InSb in magnetic field in the Voigt geometry (Fig. 1). The strength of this non-reciprocal optical effect is accurately described by Eq. (5).

The non-reciprocal reflectance effect disappears when the incident THz beam is linearly $s$-polarized, i.e., the THz electric field oscillates along the $y$ axis in Fig. 1. The reflectance of the $s$-polarized THz beam can be conveniently used as the reference measurement for the non-reciprocal $p$-polarized reflectance. Figure 2(b) shows the non-reciprocal $p$-polarized reflectance normalized by the $s$-polarized reflectance at different temperatures. The solid lines show the fitting of experimental data to Eqs. (5)-(6). We find an excellent agreement between the calculation and the measurement and list the best fitting parameters in Table I.

Given the observed non-reciprocity of reflectance for incidence angles $\pm \alpha$, it is instructive to ask whether the amplitude transmittance $t(\alpha)$ of the THz beam with incidence angles $\pm \alpha$ should be different as well. We measured the oblique incidence transmittance with $\alpha = 30^\circ$ and positive and negative magnetic fields, $B = \pm 0.18$ T and $B = \pm 0.40$ T. Figure 3 shows the measured transmitted amplitude of the $p$-polarized THz beam normalized by the $s$-polarized transmitted amplitude, as well as the transmitted amplitude calculated using Eqs. (7)-(8). The calculation and the measurement agree well and show that the oblique incidence transmittance $t(+B) = t(-B)$ and, therefore, $t(\alpha) = t(-\alpha)$. By symmetry, this
FIG. 3: Amplitude transmittance in the $p$ polarization normalized by transmittance in the $s$ polarization. The angle of incidence $\alpha = 30^\circ$. Transmittance in either polarization does not depend on the direction of magnetic field and does not exhibit non-reciprocity.

also means that transmittance $t(\alpha)$ is reciprocal, i.e., the forward and backward traveling transmitted beams experience the same transmission coefficient.

How is it that $t(\alpha) = t(-\alpha)$ at the same time as $r(\alpha) \neq r(-\alpha)$? Conservation of energy demands that $A(\alpha) + R(\alpha) + T(\alpha) = 1$, with $A(\alpha)$, $R(\alpha)$, and $T(\alpha)$ being the fractions of absorbed, reflected, and transmitted energy ($R(\alpha) = |r(\alpha)|^2$ and $T(\alpha) = |t(\alpha)|^2$). We can also write $A(-\alpha) + R(-\alpha) + T(-\alpha) = 1$. Since $T(\alpha) = T(-\alpha)$, the difference between $R(\alpha)$ and $R(-\alpha)$ is accounted for by the difference in absorption $A(\alpha)$ and $A(-\alpha)$ so that $A(\alpha) + R(\alpha) = A(-\alpha) + R(-\alpha)$. For the backward traveling beam 2 in Fig. 1, a higher fraction of energy is absorbed due to the lower reflectance. Strictly speaking, the conservation of energy only holds when all Fabry-Perot reflections within the InSb wafer are accounted for in the computed $R(\alpha)$ and $T(\alpha)$. Our Eqs. (5) and (7) do not include the Fabry-Perot reflections. Due to the high absorption close to the plasma frequency, the Fabry-Perot reflections can be neglected and the energy conservation can be applied to the main transmitted and reflected THz pulses in time domain. We also find that the relation $t(\alpha) = t(-\alpha)$ holds for the transmission of the main THz pulse as well as for the transmission that includes all of the Fabry-Perot reflections.$^{38}$

After testing the THz optical properties of InSb in magnetic field, we then designed the
FIG. 4: (a) The calculated isolation for the \( p \)-polarized THz wave for positive and negative incidence angles. Maximum isolation (bright yellow color) exceeds 35 dB. The frequency of the maximum isolation varies along the short red line from 1.96 THz at \( \alpha = 66^\circ \) to 2.02 THz at \( \alpha = 72^\circ \). (b) The calculated insertion loss of our THz isolator. The red-and-yellow line indicates the points of maximum isolation from panel (a). The average insertion loss along the bottom yellow segment is -6.2 dB. Realistic room-temperature InSb Drude parameters from Table I were used in the calculation.

THz optical isolator based on the non-reciprocal reflectance. We searched the parameter space of the incidence angles \( \alpha \) and the applied magnetic fields \( B \) to determine the best achievable optical isolator performance defined by the isolation power \( R(+\alpha)/R(-\alpha) \) and the insertion loss that is equal to \( R(+\alpha) \), the intensity reflectance in the forward direction. We used the actual room-temperature Drude parameters for InSb (Table I) and kept the magnetic field strength in the 0.0-0.5 T range that is easily supplied by small permanent
magnets. We found that the best isolator performance exceeds 35 dB in the range of incidence angles $\alpha = 60^\circ - 75^\circ$ and of applied magnetic field $B = 0.2 - 0.35$ T. The yellow arc in Fig. 4(a) shows the points of highest isolation in the $B - \alpha$ plane. The frequency of maximum isolation slowly changes along the arc: the frequency changes from 1.96 THz to 2.02 THz between $\alpha = 66^\circ$ and $\alpha = 72^\circ$ along the red line Fig. 4(a). Figure 4(b) shows the insertion loss in the same incidence angle and magnetic field range. The red-and-yellow line in Fig. 4(b) indicates the points of the highest isolation from Fig. 4(a). The average insertion loss along the yellow segment at the bottom is -6.2 dB. This performance is significantly higher than the other published experimentally demonstrated results\(^{16}\).

Figure 5(a) provides another look at the origin of the high non-reciprocal performance of our isolator: the backward amplitude reflectance is practically zero while the forward reflectance remains high at 1.96 THz frequency for $\alpha = 67^\circ$ and $B = 0.2$ T. The non-reciprocal effect is highly resonant near the 1.96 THz frequency, where the peak isolation reaches 35 dB. Despite the resonant behavior, the isolation at the fixed frequency remains very high for a range of incidence angles and magnetic fields, as shown in Fig. 5(b), where the red box indicates a region of parameters for which isolation exceeds 20 dB. Having such range of acceptable angles and magnetic fields is important for the construction of usable devices.

III. CONCLUSIONS

We explored the non-reciprocal reflectance of InSb in applied magnetic field in the Voigt geometry. We find a very high asymmetry in the $p$-polarized reflectance for positive and negative incidence angles which correspond to the forward and backward propagation directions in the THz optical isolator. At optimal incidence angles ($60^\circ - 75^\circ$) and applied magnetic fields (0.2 - 0.35 T), the isolator performance at room temperature exceeds 35 dB, which is significantly higher that the performance of the other experimentally demonstrated THz non-reciprocal devices. At the same time, the optimal magnetic field of our isolator is much more practical compared to other proposed architectures that typically require magnetic fields of several Tesla. A 0.4 T field is easily supplied by a small permanent magnet. Another advantage of our isolator is that it works directly with linearly polarized light, in contrast to the Farady-rotation-based isolator concepts that provide isolation for the cir-
FIG. 5: (a) The calculated amplitude reflectance for the $p$-polarized THz wave for positive and negative incidence angles. For the negative incidence angle, which corresponds to the backward traveling wave, the reflectance is practically zero at 1.96 THz frequency. The incidence angle $\alpha = 67^\circ$ and the magnetic field $B = 0.2$ T. (b) The calculated isolation at the fixed frequency 1.96 THz for a range of incidence angles and magnetic fields. Peak isolation exceeds 35 dB, corresponding to the situation in panel (a). The isolation remains high in a large range of incidence angles and magnetic fields. Isolation exceeds 20 dB everywhere inside the red box. Realistic room-temperature InSb Drude parameters from Table I were used in the calculation.

Circular polarization and require additional polarization converting elements. The operating frequency of the isolator can be easily tuned by temperature (Fig. 2). Finally, we emphasize the simplicity and robustness of our isolator design that does not require any micro- or nano-fabrication steps, which should make it very cost-efficient.
IV. METHODS

THz spectroscopy measurements in reflection and transmission were performed on a home-built THz time-domain spectrometer based on a modelocked femtosecond laser and photoconductive antennas for THz emission and detection. For reflection and transmission spectroscopy in magnetic field, sets of permanent neodymium magnets were installed inside a helium flow cryostat. A Hall effect Gaussmeter was used to measure magnetic field.

V. ACKNOWLEDGEMENT

The work at Tulane University was supported by the NSF Award No. DMR-1554866 and by the Carol Lavin Bernick Faculty Grant Program. The work at USF was supported by the KRISS grant GP2018-023.

* Electronic address: dtalbayev@gmail.com


38 See Supplemental Material at [URL will be inserted by publisher] for additional transmission and reflectance measurements.
Supplemental Material for
A one-way mirror: High-performance terahertz optical isolator based on magneto-plasmonics

Shuai Lin,1 Sinhara Silva,2 Jiangfeng Zhou,2 and Diyar Talbayev1,*

1Department of Physics and Engineering Physics, Tulane University, New Orleans, LA 70118, USA
2Department of Physics, The University of South Florida, Tampa, Florida, 33620-7100, USA
I. CALCULATION OF TRANSMISSION AND REFLECTION COEFFICIENTS

Figure 1 shows the geometry and defines the waves used in the calculation of the transmission and reflection coefficients of a flat InSb plate. For example, the incident wave is described by the incident electric field $E^A$ and the reflected wave is described by the electric field $E^C$. The wave traveling in the negative $z$ direction inside the plate (traveling down in Fig. 1) is described by the electric field $E^B$.

![Geometry and symbol definitions of the reflection and transmission by an InSb plate of thickness $d$.](image)

We calculate the transmission and reflection of InSb plate by solving the boundary conditions for the two boundaries of a plate at $z = 0$ and $z = -d$. We follow the procedure described in Remer et al., *Phys. Rev. B* 30 3277 (1984). In this description, the waves $E^B$, $E^C$ and $E^A$.
$E^C, E^D, \text{ and } E^E$ represent the sum of all relevant Fabry-Perot terms. We set the amplitude of the incident wave, $E_A$, is 1 and the incident angle is $\alpha$.

The wave equations inside the material is

$$k^2 \vec{E} - k(\vec{k} \cdot \vec{E}) = (\omega^2/c^2)\vec{\epsilon} \cdot \vec{E},$$  \hspace{1cm} (1)

The wave vector $k$ is $\vec{k} = (\omega/c)(\sin \alpha, 0, \kappa)$, where $\kappa = -\left(\epsilon_v - \sin^2 \alpha\right)^{1/2}$ and $\epsilon_v = \epsilon_{xx} + \epsilon_{xz}/\epsilon_{xx}$.

For a InSb plate with thickness of $d$, the boundary conditions for $z = 0$ and $z = -d$ are,

$$z = 0: \quad E^A_x + E^C_x = E^B_x + E^E_x \quad \text{and} \quad D^A_z + D^C_z = D^B_z + D^E_z, \quad (2)$$

$$z = -d: \quad E^B_x e^{-i(\omega/c)\kappa d} + E^E_x e^{i(\omega/c)\kappa d} = E^D_x \quad \text{and} \quad D^B_z e^{-i(\omega/c)\kappa d} + D^E_z e^{i(\omega/c)\kappa d} = E^D_z. \quad (3)$$

With incident field $E_A = 1$, $r = E_C/E_A = E_C$ and $t = E_D/E_A = E_D$. Then $E^A_x = \cos \alpha$, $E^C_x = r \cos \alpha$, $D^A_z = \sin \alpha$, $D^C_z = r \sin \alpha$, $E^D_x = t \cos \alpha$ and $E^D_z = t \sin \alpha$. Furthermore, because $\nabla \cdot \vec{D} = 0$ inside the plate, we obtain

$$\sin \alpha D^B_x + \kappa D^B_z = 0 \quad \text{and} \quad \sin \alpha D^E_x - \kappa D^E_z = 0, \quad (4)$$

From Eqs. (2)-(4), we calculate the reflection and transmission coefficients $r$ and $t$:

$$r = -\frac{\epsilon_{xx} \epsilon_v \cos \alpha}{\epsilon_{xx} \sin \alpha + \epsilon_{xz} \kappa} \frac{1 + b}{1 + a}, \quad (5)$$

$$t = \frac{1 + r}{1 + a} \left( e^{-i(\omega/c)\kappa d} + a e^{i(\omega/c)\kappa d} \right), \quad (6)$$

where

$$a = b \frac{\epsilon_{xx} \sin \alpha - \epsilon_{xx} \kappa}{\epsilon_{xx} \sin \alpha + \epsilon_{xx} \kappa}, \quad (7)$$

$$b = -e^{-2i(\omega/c)\kappa d} \frac{\epsilon_{xz} \sin \alpha + \epsilon_{xx} \kappa + \epsilon_{xx} \epsilon_v \cos(\alpha)}{\epsilon_{xz} \sin \alpha - \epsilon_{xx} \kappa + \epsilon_{xx} \epsilon_v \cos(\alpha)}. \quad (8)$$

The $r$ and $t$ given by Eqs. (5) and (6) include all of the Fabry-Perot reflections within the InSb plate.

We now calculate $r$ and $t$ of the plate without the Fabry-Perot reflections. This corresponds to the reflection and transmission of the main THz pulse in time domain, without the inclusion of the subsequent Fabry-Perot echoes. The boundary conditions without the echoes for $z = 0$ and $z = -d$ are:

$$z = 0: \quad E^A_x + E^C_x = E^B_x \quad \text{and} \quad D^A_z + D^C_z = D^B_z, \quad (9)$$
\[ z = -d : \quad E_x^B e^{-i\omega/c} + E_x^E = E_x^D \quad \text{and} \quad D_z^B e^{-i\omega/c} + D_z^E = D_z^D. \]  

We calculate the reflection coefficient \( r_p \) and transmission coefficient \( t_p \) from Eqs. (9), (10), and (4):

\[
r_p = \frac{\epsilon_{xz} \sin \alpha + \epsilon_{xx} (\kappa + \epsilon_v \cos \alpha)}{\epsilon_{xz} \sin \alpha + \epsilon_{xx} (\kappa - \epsilon_v \cos \alpha)} \frac{\epsilon_{xz} \sin \alpha + \epsilon_{xx} (\kappa - \epsilon_v \cos \alpha)}{\epsilon_{xz} \sin \alpha + \epsilon_{xx} (\kappa + \epsilon_v \cos \alpha)},
\]

\[
t_p = e^{-i\omega/c} \frac{(1 + r_p)(1 - r_p)(a - b)}{a(1 + r_p) - b(1 - r_p)}.
\]

Equations (11) and (12) reproduce the Equations (5) and (7) from the main part of the article. They also produce equivalent computational results to Eqs. (5) and (6) in the frequency ranges with high absorption.

II. SUPPLEMENTARY DATA

FIG. 2: Normal incidence transmission spectra at different temperatures and zero magnetic field. Symbols - measurement; solid lines - theoretical fit using the dielectric function of Eqs. (1)-(4) from the main text.
FIG. 3: Amplitude reflectance in the $p$ polarization normalized by reflectance in the $s$ polarization for positive and negative magnetic field. $B=0.4$ T as measured by the Gaussmeter. The $s$-polarized reflectance does not depend on the direction of magnetic field and does not exhibit the non-reciprocity. Symbols - measurement, solid lines - calculation using Equations (5) and (6) from the main text.

III. NONRECIROCAL REFLECTANCE OF GAAS

* Electronic address: dtalbayev@gmail.com
FIG. 4: The calculated amplitude reflectance for the $p$-polarized THz wave for positive (red) and negative (blue) incidence angles on GaAs at room temperature. The incidence angle is $65^\circ$ and the magnetic field $B=2.6$ T.