Polarization-independent tunable terahertz slow light with electromagnetically induced transparency metasurface

Koijam Monika Devi1, Arun Jana1, Ajinkya Punjal2, Nityananda Acharyya1, Shriganesh S Prabhu2, and Dibakar Roy Chowdhury1,*
1 École Centrale School of Engineering, Mahindra University, Hyderabad 500043, India
2 Tata Institute of Fundamental Research, Mumbai 400005, India
* Author to whom any correspondence should be addressed
E-mail: dibakar.roychowdhury@mahindrauniversity.edu.in
Keywords: dynamically tunable, slow light, polarization independent, terahertz, metasurfaces

Supplementary material for this article is available online

Abstract
Tunable slow light systems have gained much interests recently due to their efficient control of strong light–matter interactions as well as their huge potential for realizing tunable device applications. Here, a dynamically tunable polarization independent slow light system is experimentally demonstrated via electromagnetically induced transparency (EIT) in a terahertz (THz) metasurface constituted by plus and dimer-shaped resonators. Optical pump-power dependent THz transmissions through the metasurface samples are studied using the optical pump THz probe technique. Under various photoexcitations, the EIT spectra undergo significant modulations in terms of its resonance line shapes (amplitude and intensity contrast) leading to dynamic tailoring of the slow light characteristics. Group delay and delay bandwidth product values are modulated from 0.915 ps to 0.42 ps and 0.059 to 0.025 as the pump fluence increases from 0 to 62.5 nJ cm$^{-2}$. This results in tunable slow THz light with group velocities ranging from $2.18 \times 10^5$ ms$^{-1}$ to $4.76 \times 10^5$ ms$^{-1}$, almost 54% change in group velocity. The observed tuning is attributed to the photo-induced modifications of the optoelectronic properties of the substrate layer. The demonstrated slow light scheme can provide opportunities for realizing dynamically tunable slow light devices, delay lines, and other ultrafast devices for THz domain.

1. Introduction
The quest for an effective way of manipulating light–matter interactions has driven most of the research in photonics. To achieve an efficient control over the optical response of a system is of crucial significance not only from a fundamental perspective but also from an applications’ point of view [1–3]. In this regard, slow light systems have gained much attention recently, as it supports stronger light–matter interactions and provides extra control over the interaction’s bandwidth [4–6]. Usually, slow light is termed as light with extremely low group velocity derived by $v_g = d\omega/dk$ where, $\omega$ is the angular frequency and $k$ is the wave vector of light [4, 6]. As such, slow light enables delaying of a light pulse along with spatial compression of the pulse ultimately enhancing the linear/nonlinear optical effects in a system [5]. Over the years, slow light has been achieved in quantum systems [7–9] as well as in classical artificial composite systems like metamaterials [10–12], photonic crystals [13, 14], and plasmonic systems [15], etc. Among these systems, metamaterials/metasurfaces have been investigated for the realization of slow light through electromagnetically induced transparency (EIT) phenomenon [10–12] in different frequency regions across the electromagnetic spectrum. In metamaterials, EIT arises due to the coupling among bright–bright [16], bright–quasi dark [17], and bright–dark modes [12, 18]. Generally, the resonance which is directly excited by the incident light is defined as the bright mode, while the weakly excited resonance is termed as the dark mode [19]. The interference between the modes give rise to a narrow transparency window along with an
increased transmission which is often accompanied by strongly modified dispersions ultimately leading to a reduced group velocity of the incident light (i.e., slow light) within the transparency band [7, 12].

So far, EIT has been investigated using several metamaterial structures including metal strips [12, 20], split ring resonators [21, 22], circular ring [23], etc or a combination of these structures [18] for the development of potential device applications such as sensors [24], filters and modulators [25], absorbers [26], slow light devices [27, 28], etc. However, the performance of these devices are often limited due to the restricted tunability associated with the passive nature of the metamaterial structures. In metamaterials, passive control of EIT is usually attained by changing the geometrical parameters of the structure which requires fabrication of multiple samples often leading to complexities during device fabrications. In this regard, actively tunable metamaterials have been employed to circumvent the limitations associated with passive structures thus, enhancing the efficiency of the potential devices [29–31]. Recently, several efforts have been made to achieve active tuning of EIT by incorporating active elements like semiconductor materials [29, 32], graphene [30, 33–35], nonlinear elements [36], phase changing materials [37], etc into the structure. Another demonstrated method of achieving tunable EIT response is through the photoexcitation of metamaterials by an optical pump beam [29, 35, 38]. The active EIT responses achieved in these systems can lead to the realization of different tunable practical metadevices [39–41] which in turn, can benefit the so called terahertz (THz) gap which is still suffering due to the lack of efficient functional devices [3, 42–45]. In particular, dynamically tunable slow light based on EIT in metamaterials could be utilized to develop tunable delay lines [29] and communication channels [21] at the THz band that can be advantageous for 6G communication systems. Additionally, numerous ultrafast devices can also be practically realized using tunable EIT in THz metamaterials [39, 46]. As such, there is considerable interest regarding dynamically tunable EIT and slow light as it offers great opportunities for the development of various tunable devices at THz frequencies.

Therefore, in this article, we experimentally demonstrate dynamically tunable slow light behaviour in a metasurface displaying the EIT phenomenon at THz frequencies. Although, studies on tunable slow light has been reported earlier, majority of the investigations have been carried out using polarization dependent systems wherein tuning is achieved for a specific polarization of the incident THz radiation [29–31]. However, achieving a polarization independent response may be desirable for device applications as it would enable identically strong variation of slow light for different incident polarizations ultimately enhancing the device’s functionality. Motivated by this aspect, the proposed metasurface (which comprises of plus and dimer structures) is strategically designed to be symmetric for x- and y-linearly polarized THz light thus, resulting in a polarization independent EIT response which in turn, leads to polarization independent slow light for the two orthogonal polarizations. A standard photolithography method is employed for the fabrication of the metasurface samples which are then characterized by using the optical pump terahertz probe (OPTP) spectroscopy technique [47–49]. In the proposed metasystem, the interference of bright-dark modes gives rise to the EIT phenomenon. This EIT response is probed under variable pump fluences and a modulation of the EIT spectra is achieved in terms of its amplitude and intensity contrast at different fluences of the incident pump beam. Further, a quantitative tuning of the slow light properties such as group delay, group index, and delay bandwidth product (DBP) are achieved in the system with increasing pump fluences. The article is arranged as follows: the metamaterial design is discussed in section 2 while section 3 provides a discussion on the obtained results. Section 4 describes the dynamic tailoring of the slow THz light, section 5 provides a brief conclusion and section 6 describes the experimental methods employed during the study.

2. Metasurface design and characterization

We design a metasurface structure capable of demonstrating dynamically tunable slow light features by means of the EIT phenomenon at THz frequencies. The proposed design of the THz metasurface is depicted in figure 1. Figure 1(a) describes the artistic illustration for the OPTP measurements of the THz transmission characteristics of the metasurface, wherein the metamaterial array is simultaneously illuminated by the incident THz beam as well as the optical pump beam with different fluences. The inset of figure 1(a) represents the enlarged version of the subwavelength meta-atom which comprises of a plus structure and four dimer structures made of aluminium on a silicon substrate in orthogonal fashion. Here, we define the periodicity of the meta-atom by the parameters \( P_x (P_y) \) in the \( x- \) (\( y- \)) direction. \( L \) signify the length of the arms of the plus structure while the outer dimension of each dimer structure is denoted by \( a \). The width and thickness of the plus and the dimer structures are denoted by \( w \) and \( t \), whereas \( d \) indicates the separation between the plus structure and each of the dimer structures. \( h \) denotes the substrate thickness while \( h' \) denotes the thickness of the photodoped layer of the silicon substrate (i.e., penetration depth of silicon around 1000 nm). In our study, we have taken the parameter values as \( P_x = P_y = 128 \) μm,
Figure 1. Design of the proposed THz metasurface. (a) Schematic illustration of OPTP characterizations of the metasurface samples. Inset illustrates an enlarged view of the meta-atom for the EIT metasurface array. The incident E-field polarization is indicated by the green arrow. Subwavelength meta-atom of the fabricated (b) plus structure and (c) dimer structures. (d) Fabricated sample for the metasurface array. The inset shows the enlarged version of the meta-atom wherein the dimers are sequentially numbered from the top left resonator as 1, 2, 3, and 4 in a clockwise manner.

$L = 83 \, \mu m$, $a = 34 \, \mu m$, $w = 5 \, \mu m$, $h = 500 \, \mu m$ and $t = 200$ nm. The optical response of proposed design is initially investigated by employing the finite element method based frequency domain solver in CST Microwave Studio. The THz transmission characteristics for metasurface array are numerically calculated under normal incidence using appropriate boundary conditions in the $x$, $y$, and $z$-directions. A mesh grid $\sim \lambda/10$ ($\lambda \sim$ incident wavelength) is chosen and Floquet ports are employed for the generation as well as detection of the THz radiations.

Here, it must be noted that the proposed metasurface array is designed to be structurally symmetric for the $x$- and $y$-linearly polarized incident light, due to which, the EIT effect displayed by the proposed metasurface supposed to be polarization independent for the two orthogonal polarizations of the incident THz light [18]. The metasurface samples are then fabricated by utilizing a standard photolithography technique (see more details of sample fabrication in the experimental section). For thorough investigations, three different sets of metasurface samples are fabricated wherein the first and second samples consist an array of plus and four dimer structures, respectively while the third sample consists of an array of plus coupled to dimer structures (figure 1). The optical microscopic images of the meta-atom of the fabricated plus structure and dimer structures are shown in figures 1(b) and (c) while, figure 1(d) illustrates the fabricated EIT metasurface sample with the inset displaying the enlarged view of the meta-molecule (unit cell) of the metasurface array. Thereafter, the fabricated metasurface samples are characterized by employing an electro-optic time resolved OPTP spectroscopy technique (see more details in the experimental section) wherein the incident THz electric field is along the vertical arm of the plus structure. The THz transmissions are measured under various optical pump fluences and the dynamic tunability of the proposed metasurface is examined (figure 2).

3. Results and discussions

The optical tuning of the THz transmissions through the metasurface samples are probed with the increase in the pump fluences when the incident THz electric field is parallel to the vertical arm of the plus structure. The THz transmission characteristics measured using the OPTP setup at various pump fluences are illustrated in figure 2. THz transmission spectra of the three metasurface samples (figures 1(b)–(d)) are examined separately to understand the occurrence and tuning of the EIT phenomenon in details. The columns figures 2(i)–(iii) represents the transmission spectra for the plus structure, dimer structure and the coupled structure respectively. Row figure 2(a) represents the corresponding optical microscopic images of the meta-atom of the different metasurface arrays while the rows figures 2(b)–(d) represent THz transmission spectra corresponding to different pump fluences (i.e., 0 nJ cm$^{-2}$, 2.5 nJ cm$^{-2}$, and 62.5 nJ cm$^{-2}$). The black dashed lines indicate the experimentally measured THz transmissions while the
Figure 2. Optical tuning of EIT response at different pump fluences. (i) Transmission spectra for (a) plus structure at 
(b) fluence = 0 nJ cm\(^{-2}\), \(\sigma = 0.1 \text{ s m}^{-1}\), (c) fluence = 2.5 nJ cm\(^{-2}\), \(\sigma = 20 \text{ s m}^{-1}\), and (d) fluence = 62.5 nJ cm\(^{-2}\), 
\(\sigma = 300 \text{ s m}^{-1}\). (i) Transmission spectra for (a) dimer structure with transmission at (b) fluence = 0 nJ cm\(^{-2}\), \(\sigma = 0.1 \text{ s m}^{-1}\), 
(c) fluence = 2.5 nJ cm\(^{-2}\), \(\sigma = 20 \text{ s m}^{-1}\), and (d) fluence = 62.5 nJ cm\(^{-2}\), \(\sigma = 300 \text{ s m}^{-1}\). And, EIT response for (a) coupled metasurface structure at (b) fluence = 0 nJ cm\(^{-2}\), \(\sigma = 0.1 \text{ s m}^{-1}\), (c) fluence = 2.5 nJ cm\(^{-2}\), \(\sigma = 20 \text{ s m}^{-1}\), and 
(d) fluence = 62.5 nJ cm\(^{-2}\), \(\sigma = 300 \text{ s m}^{-1}\). The black dashed and red solid lines indicate the experimentally measured and 
numerically calculated THz transmissions. The green arrows indicate the direction of electric field in probing THz.

red solid lines signify the numerically calculated transmissions. As evident from the figure, the transmission 
spectra for the dipole (plus) structure displays a usual dipolar resonance dip at \(f \sim 0.62 \text{ THz}\) while, the 
dimer structure exhibits resonance at \(f \sim 0.63 \text{ THz}\) (almost same frequency). For the \(y\)-linearly polarized incident THz light, only the vertical arm of plus resonator (basically dipole) is excited thus, contributing to 
the bright mode (radiative) of the system. On the other hand, the incident THz light excites the first and the 
third dimer structures while, the second and fourth dimer resonators remain completely unexcited 
(non-radiative). Thus, the second and fourth dimer resonators ultimately act as the dark mode of the 
system for this particular incident polarization. As the plus and dimer resonators are coupled to each other 
to form the EIT metasurface structure (figure 1(d)), the resulting metasurface exhibits the EIT 
phenomenon. Here, the vertical dipole along with the pair of dimer resonators (2nd and 4th dimer) 
contribute to the excitation of EIT effect wherein a narrow transparency region ranging from 0.53 THz to 
0.74 THz is induced with an enhanced transmission peak occurring at \(f \sim 0.6 \text{ THz}\) (figure 2). The EIT in 
the coupled metasurface structure occurs due to bright-dark mode interference in the system and it is 
polarization independent for the two orthogonal incident polarizations due to the structural symmetry 
involved in the metasurface design (figure 1).

Under the variable pump fluences, a modulation in the THz transmissions is achieved in terms of the 
amplitude and intensity contrast of the corresponding transmission spectra. The intensity contrast for the 
resonances of the metasurface structures calculated from the measured THz transmissions as well the 
numerically simulated transmissions are listed in table 1. At a pump fluence of 0 nJ cm\(^{-2}\), the resonances 
have an intensity contrast values of 0.422 and 0.321 for the plus and the dimer structures. For this case, the 
intensity contrast for the first and the second resonance dip of the EIT spectra has values of 0.169 and 0.372.
With increase in the laser pump fluence, it is observed that the THz transmissions are shifted towards lower amplitudes followed by a reduction in the intensity contrast of the resonance dips. For a fluence of 2.5 nJ cm$^{-2}$ the plus and the dimer structures have intensity contrast values of 0.340 and 0.252, while intensity contrast of 0.155 and 0.322 are obtained for the first and the second resonance dips of the EIT spectra. Finally, at a pump fluence of 62.5 nJ cm$^{-2}$, an obvious reduction in resonance amplitudes as well as huge decrease in the intensity contrast is observed for the plus and dimer structures with corresponding values as 0.29 and 0.08. Subsequently, the amplitude and intensity contrast is greatly reduced to 0.062 and 0.208 for the first and the second resonance dips of the EIT spectra. The observed tuning of the THz transmission spectra is attributed to the photodoping of the silicon substrate in the proposed structure under various fluences. For case I: fluence $= 0$ nJ cm$^{-2}$, there is no photoexcitation across the substrate and thus, a transmission spectrum with prominent resonance features are observed for each of the three metasurface samples. As the pump fluence is increased, charge carriers are excited across the substrate layer just underneath the metasurface patterns causing an increase in the conductivity of the photodoped layer [50, 51]. This causes a modulation in the resonance strength of the metasurface samples triggering a huge reduction in the intensity contrast of the transmission spectra ultimately leading to a diminished EIT phenomenon for the third case (fluence $= 62.5$ nJ cm$^{-2}$).

The modulation of the measured THz transmissions is further corroborated using numerically simulated transmissions which is denoted by the red lines in figure 2. In the numerical simulations, the silicon substrate is modelled as a lossless dielectric with $\varepsilon_{Si} = 11.7$ while aluminium is taken as a lossy metal with a dc conductivity of $3.72 \times 10^7$ S m$^{-1}$. Further, to incorporate the measured effect of carrier excitations under the variable pump fluences into the design of the metasurface, we additionally model a thin photodoped silicon layer ($h' \sim 1000$ nm) with variable conductivity just underneath the patterned array of the structure as depicted in the inset of figure 1(a). The different values of conductivity corresponding to the pump fluences of $0$ nJ cm$^{-2}$, 2.5 nJ cm$^{-2}$, and 62.5 nJ cm$^{-2}$ are extracted from the measured THz transmissions as $0.1$ S m$^{-1}$, $20$ S m$^{-1}$ and $300$ S m$^{-1}$ respectively (see supplementary information and figure S1 there) (https://stacks.iop.org/NJP/24/093004/mmedia). These experimentally extracted conductivities caused by different photo doping of the thin substrate layer are then employed in the design and study of the optical responses of the different metasurface samples. When $\sigma = 0.1$ S m$^{-1}$, the transmission dip has an intensity contrast value of 0.771 and 0.641 for the plus and the dimer structure while the first and the second resonance dips of the EIT spectra has intensity contrast values of 0.578 and 0.665. As the conductivity is increased to $\sigma = 20$ S m$^{-1}$, the plus and the dimer structures have intensity contrast values of 0.698 and 0.541 while the first and the second dips of the EIT spectra has an intensity contrast of 0.402 and 0.539. Similar to measured transmission, the intensity contrast value undergoes significant reduction for $\sigma = 300$ S m$^{-1}$, wherein an obvious shift in the amplitude as well as large change in the intensity contrast is observed for the plus, dimer, and EIT structures. The obtained intensity contrast values are 0.37 and 0.223 for the plus and the dimer structures while we obtain 0.029 and 0.206 for the first and the second resonance dips of the EIT spectra. The numerically achieved THz transmissions agrees well with our experimental transmission responses (see table 1) with minor discrepancies. The observed discrepancies between the experimental and the simulations results are owed to two main factors. First, the existing uncertainties during sample fabrication may result in a metasurface having a slightly different geometrical profile from that of parameter values chosen nominally in the numerical simulations [52]. Second, the transmitted time-domain THz pulses are truncated in order to remove the contributions of the etalon effect [53] which leads to loss of some information in the frequency domain response obtained via fast Fourier transformation (FFT). This eventually results in reduced Q-factor captured in the transmission spectra as seen in figure 2.

To obtain deeper insights on the underlying physical mechanisms for the excitation and modulation of the EIT effects, we further examine the surface current profiles of the studied metasurface at extreme cases of photoexcitations. Figure 3 shows the distribution of surface currents at the first transmission dip,
transmission peak and second transmission dip of the EIT transmission spectra for $\sigma = 0.1 \text{ S m}^{-1}$ (figures 3(a)–(c)) and $\sigma = 300 \text{ S m}^{-1}$ (figures 3(d)–(f)), respectively, wherein the directions of the surface currents are indicated by the black arrows. When the incident electric field is along $y$-axis (indicated by green arrow in figure 3), the vertical arm of the plus structure (basically dipole) is excited which then behave as the bright mode of the system. Conversely, the second and fourth dimers are not directly excited by the incident THz as their resonator gaps are perpendicular to incident field polarization. Hence, the second and fourth dimer resonators act as dark mode of the metasurface system. When these resonators are coupled through near-field electromagnetic interactions, the EIT phenomenon consequently arises due to the near-field bright-dark mode hybridizations in the coupled structure. Here, the electric dipolar mode of the vertical arm excites the fundamental LC or magnetic dipole mode in the 2nd and 4th dimer structures. From figure 2, it is evident that the EIT response in the system is prominent in the absence of photoexcitation ($\sigma = 0.1 \text{ S m}^{-1}$). For this case, at the first transmission dip ($f = 0.543 \text{ THz}$), there is excitation of dipolar surface currents in the vertical arm of the plus structure as shown by the black arrows in figure 3(a). These dipolar currents further excite clockwise and anticlockwise circular currents in the second and fourth dimer structures, respectively. However, at the transmission peak of the EIT spectra at $f = 0.602 \text{ THz}$ (figure 3(b)), it is observed that the surface currents are sparsely distributed in the vertical arm of the plus structure indicating a suppression of the dipolar bright mode but prominent current in the dark resonators (2nd & 4th dimers). This suppression of the bright mode and excitation of the dark mode gives rise to the enhanced transmission peak within the EIT window in the studied metasystem. For the second transmission dip at $f = 0.747 \text{ THz}$ (figure 3(c)), the induced dipolar current of the vertical arm is opposite in nature with respect to the circular surface currents in the second and fourth dimers, respectively.

These surface current distributions are further examined for higher pump fluences corresponding to higher conductivities of the photodoped substrate layer. Under higher photoexcitation (62.5 nJ cm$^{-2}$), a huge amount of charge carriers is generated across the substrate layer just underneath the metasurface pattern which subsequently increases the conductivity of the photodoped layer. This photoexcited layer becomes highly conductive with the increase in the pump fluences due to which the optical response of the metasurface array suffers a significant alteration, which could be clearly understood from the calculated surface current profiles for $\sigma = 300 \text{ S m}^{-1}$ shown in figures 3(d)–(f). When $\sigma = 300 \text{ S m}^{-1}$, the dipolar currents of vertical arm excite anticlockwise and clockwise surface currents in the second and fourth dimer resonators at the first transmission dip $f = 0.523 \text{ THz}$ (figure 3(d)). Similar to the previous case, at the frequency $f = 0.595 \text{ THz}$, the bright mode is suppressed resulting in EIT peak and the surface currents are distributed in the second dimer, and the fourth dimer structures (figure 3(e)). Again, for the second resonance dip at $f = 0.73 \text{ THz}$, the vertical dipolar current is in opposite phase with circular surface currents in the dark dimer resonators. Here, it is evident from the figures that the surface currents are distributed in similar fashion in the bright and dark resonators. However, the strength and density of the surface current distributions are comparatively much feebler than that of the first case of no
Figure 4. Dynamic tuning of slow THz light. (a) Calculated group delay ($\tau_g$) from the measured THz data, (b) calculated group index ($\eta_g$) from the measured data. The insets of (a) and (b) shows the corresponding numerically calculated group delay and group index.

Table 2. Calculated $\tau_g$ and DBP at various pump fluences.

| Fluence (nJ cm$^{-2}$) | $f$ (THz) | $\tau_g$ (ps) | $\Delta f$ (THz) | DBP = $\tau_g \times \Delta f$ |
|------------------------|-----------|---------------|------------------|-------------------------------|
| 0                      | 0.589     | 0.915         | 0.065            | 0.059                         |
| 2.5                    | 0.593     | 0.873         | 0.065            | 0.056                         |
| 62.5                   | 0.604     | 0.420         | 0.060            | 0.025                         |

photoexcitation. Consequently, there is a reduction of the intensity contrast of the transmission spectra ultimately resulting in the fading of the EIT response.

4. Dynamic tuning of slow light features

In this studied metalensystem, the enhanced transmission of the tunable EIT spectra is accompanied by strongly modified dispersive properties which can eventually be harnessed to realize slow light device applications. To highlight the device aspects of the proposed structure, we demonstrate the dynamic tailoring of slow light characteristics like the group delay ($\tau_g$), group refractive index ($\eta_g$), and DBP w.r.t. different values of the optical pump fluences. For an optical system, the group delay is referred as the time a light pulse is trapped inside the system. This delay is defined as $\tau_g = -\frac{d\phi}{d\omega}$, where $\phi$ denotes the phase and $\omega$ is the incident angular frequency [21]. Further, the group refractive index ($\eta_g$) can be obtained using the relation $\eta_g = \frac{c}{D\tau_g}$, where $D$ is the thickness of the metasurface and $c \sim 3 \times 10^8$ m s$^{-1}$ is the speed of light [30]. It is noteworthy to mention that slow light is achieved for a normally dispersive region indicated by positive values of the group refractive index, while a negative index value signifies anomalous dispersion thus, leading to the fast light phenomenon [6]. The experimentally calculated group delay and group index values corresponding to different pump fluences are illustrated in figure 4. The blue traces represent the group delay and index for the case of no photoexcitation while the red and green solid lines signify delay and indices corresponding to a fluence of 2.5 nJ cm$^{-2}$ and 62.5 nJ cm$^{-2}$, respectively. From the figure, it is clear that a tuning of the group delay as well as group indices are achieved with an increasing value of the pump fluences. Table 2 depicts the quantitative variations of group delay as a function of the different pump fluences. It is observed that the group delay of the system is altered from 0.915 ps to 0.42 ps with increasing photoexcitation. Furthermore, the group index is varied within the range of 1372 to 630 resulting in dynamically tuned slow THz with minimum group velocities ($\nu_g$) [23] ranging from $2.18 \times 10^5$ m s$^{-1}$ to $4.76 \times 10^5$ m s$^{-1}$ (tuning of $\sim$54%) with variable pump fluence. The experimentally calculated values agree well with the corresponding numerical results plotted in the insets of figures 4(a) and (b).

Furthermore, the proposed tunable slow light system can also have device applications focussed towards the communication sector. To demonstrate this aspect, we also calculated the DBP of the structure which is usually defined as the product of delay ($\tau_g$) and bandwidth ($\Delta f$) [21]. DBP is a number which generally represents the amount of signal information that can be transmitted through a network at any given time. For practical applications, achieving a dynamically tunable DBP is of great significance, since a device with a tunable DBP would enable a more efficient and tunable routing of the signal data through the network. Here, in the proposed metasurface, a dynamic tuning of DBP with values ranging from 0.059 to 0.025 is achieved by varying the pump fluences (0–62.5 nJ cm$^{-2}$). The calculated values of DBP w.r.t. variable pump fluences are listed in table 2. The observed tuning of the slow THz light characteristics is the consequence of
the intensity contrast modulations of the EIT spectra caused by the modified electronic properties of the photo-excited substrate in the system. It must also be noted that the tunable slow THz light achieved in our system is polarization independent for the two orthogonal polarizations of incident THz light due to the symmetric nature of the metasurface array (figure 1). Consequently, the demonstrated tunable slow light devices offer an enhanced performance in terms of its polarization independent dynamic tunability and as compared to the earlier reported polarization dependent slow light systems [29, 31, 33, 36]. Therefore, results obtained during the course of this study could provide new opportunities for realizing tunable slow light devices ultimately benefitting THz photonic technology.

5. Conclusions

In conclusion, optical tuning of polarization independent slow light is experimentally realized by employing EIT effects in a specially designed complex metasurface operating at THz frequencies. The proposed metasurface structure comprising of plus and dimer structures possess a structural symmetry for the x- and y-linearly polarized (orthogonal polarizations) THz probing beam. The metasurface samples are fabricated using standard photolithography technique and characterized at different strengths of optical pump fluences. With increase in pump fluence, the intensity contrast of the THz transmissions of the plus and dimer structures get significantly modulated, leading to a tunable EIT response. Numerically simulated surface current distributions provide deeper insights into the interplay of electromagnetic fields among the different constituents of the metasurface structure. Further, typical slow light characteristics like the group delay, group index, and DBP are extracted (experimentally and numerically) and the dynamic tunability of slow light is probed w.r.t. the variable pump fluences. The calculated group delay and DBP are 0.915 ps and 0.059, respectively for a pump fluence of 62.5 nJ cm$^{-2}$ (highest fluence we could achieve), we obtain the corresponding values as 0.42 ps and 0.025, respectively. Additionally, group velocity of propagating THz is tuned within the range of 2.18 × 10$^5$ m s$^{-1}$ to 4.76 × 10$^2$ m s$^{-1}$ with varying pump powers. Dynamic tuning of the EIT response and slow THz light is accomplished as a consequence of the photo-induced modifications of the substrate’s properties in the designed metasurface. The measured THz transmissions and slow light features are well corroborated with numerically obtained results. Current study could open routes for realizing tunable delay lines, communication channels and other ultrafast devices ultimately advancing THz photonics.

6. Experimental section

Sample fabrication: the metasurface samples are fabricated using standard UV-based photolithography technique comprising of multiple step-by-step processes in a clean room environment. Fabrication of samples is done on a highly resistive silicon substrate (resistivity > 5000 Ω cm) having a thickness ∼500 μm. First, a positive photoresist is deposited on the polished side of a cleaned silicon wafer ((100) orientation) with the help of spin coating process [54]. Then, the periodic array of the metasurface is patterned on the photoresist by means of the UV photolithography followed by a development process. Afterwards, a thin layer of aluminium metal (t ∼ 200 nm) is deposited on the developed sample by employing electron beam thermal evaporation technique. This is followed by the lift-off process using an acetone solution which ultimately reveals the desired metasurface array. The fabricated metasurface samples acquire an area ∼8 × 8 mm$^2$.

OPTP measurements: thereafter, the fabricated metasurface samples are characterized by employing an electro-optic time resolved OPTP spectroscopy technique wherein the incident THz electric field is along the vertical arm of the plus structure. The indigenously developed OPTP set up consists of a 4-lens (Tydex) configuration, wherein a Tisapphire laser pulse (80 MHz repetition rate with a central wavelength ∼800 nm) is split into two parts: first part is used for generation of THz using a photoconductive antenna, second part is further split into two parts: one of which is used for detection via standard electro-optic technique using a ZnTe crystal, while the other part is used to optically excite the metasurface sample (pump beam). A translational stage is utilized in order to precisely control the delay between the THz generation and detection beam. The optical pump beam is spatially and temporally overlapped onto the metasurface sample with the focussed THz probe beam and the spot size of the optical pump beam is kept larger than that of the THz beam to attain a uniform excitation of the metasurface array. Here, the ultrafast laser excites a transient current in the emitter which produces electromagnetic wave packets in the THz range incident on the sample. Additionally, the incident optical beam generates a huge amount of charge carriers across the substrate’s surface. Subsequently, the incident THz pulse suffers a modulation while passing through the sample which is then probed by the detector. The transmitted THz signal through the
metasurface sample is then measured in time domain, which is further transformed into frequency domain THz transmission spectra through the FFT. The measured transmitted pulses are normalized by using a bare silicon reference of the same dimensions at the same pump fluences.

Acknowledgments

Author SSP acknowledges support from TIFR vide BRNS Grant RTI4003. Authors SSP and DRC acknowledge partial support from BRNS Project 58/14/32/2019-BRNS/11090.

Data availability statement

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

ORCID iDs

Arun Jana  
https://orcid.org/0000-0001-9860-9196
Ajinikya Punjal  
https://orcid.org/0000-0002-3053-2134
Dibakar Roy Chowdhury  
https://orcid.org/0000-0002-2129-0807

References

[1] Chen Z and Segev M 2021 eLight 1 1
[2] Walia, Shah C M, Gutruf P, Nili H, Chowdhury D R, Withayachumnankul W, Bhaskaran M and Sriram S 2015 Appl. Phys. Rev. 2 011303
[3] Xiao S, Wang T, Liu T, Zhou C, Jiang X and Zhang J 2020 J. Phys. D: Appl. Phys. 53 503002
[4] Khurgin JB and Tucker R S 2018 Slow Light: Science and Applications (Boca Raton, FL: CRC Press)
[5] Krauss T F 2008 Nat. Photon. 2 448
[6] Milošević P W 2004 Fast Light, Slow Light and Left-Handed Light (Boca Raton, FL: CRC Press)
[7] Boller K-J, Imamoglu A and Harris S E 1991 Phys. Rev. Lett. 66 2593
[8] Harris S E, Field J E and Kasapi A 1992 Phys. Rev. A 46 R29
[9] Phillips D F, Fleischhauer A, Mair A, Walsworth R L and Lukin M D 2001 Phys. Rev. Lett. 86 783
[10] Papasimakis N and Zel'dovich N I 2009 Opt. Photon. News 20 22
[11] Wu C, Khmelnitsev A B and Shevets G 2011 Phys. Rev. Lett. 106 107403
[12] Zhang S, Genov D A, Wang Y, Liu M and Zhang X 2008 Phys. Rev. Lett. 101 047401
[13] Arregui G, Gomis-Bresco J, Sotomayor-Torres C M and Garcia P D 2008 Phys. Rev. A 77 033810
[14] Baba T 2008 Nat. Photon. 2 465
[15] Gan Q, Fu Z, Ding Y J and Bartoli F J 2008 Phys. Rev. Lett. 100 256803
[16] Yahiaoui R, Burrow J A, Mekonen S M, Sarangan A, Mathews J, Agha I and Searles T A 2018 Phys. Rev. B 97 155403
[17] Li H-m, Liu S-b, Liu S-y and Zhang H-f 2014 Appl. Phys. Lett. 105 133514
[18] Devi K M, Sarma A K, Chowdhury D R and Kumar G 2017 Opt. Express 25 10484
[19] Karmakar S, Kumar D, Pal B P, Varshney R K and Roy Chowdhury D 2021 Opt. Lett. 46 1365
[20] Rana G, Deshmukh P, Palikarivala S, Gupta A, Duttagupta S, Prabhu S, Achanta V and Agarwal G 2018 Phys. Rev. Appl. 9 064015
[21] Manjappa M, Chaim S-Y, Cong L, Betsiol A A, Zhang W and Singh R 2015 Appl. Phys. Lett. 106 181101
[22] Xu N, Manjappa M, Singh R and Zhang W 2016 Adv. Opt. Mater. 4 1179
[23] Wang J, Yuan B, Fan C, He J, Ding P, Xue Q and Liang E 2013 Opt. Express 21 25159
[24] Liu N, Weiss T, Mesch M, Langguth L, Eigenhauser U, Hirschler M, Sönntgen C and Giessen H 2010 Nano Lett. 10 1103
[25] Zografopoulos D C, Swillam M and Beccherelli R 2016 IEEE Photon. Technol. Lett. 28 818
[26] Okamoto K, Tanaka D, Degawa R, Li X, Wang P, Ryuzaki S and Yamada K 2016 Sci. Rep. 6 36165
[27] Lai G, Liang R, Zhang Y, Bian Z, Yi L, Zhao G and Zhao R 2015 Opt. Express 23 6554
[28] Yannopapas V, Paspalakis E and Vitanov N V 2009 Phys. Rev. B 80 053104
[29] Gu J et al 2012 Nat. Commun. 3 1151
[30] Kumar D, Devi K M, Kumar R and Roy Chowdhury D 2021 Opt. Commun. 491 126949
[31] Yahiaoui R, Manjappa M, Srivastava Y K and Singh R 2017 Appl. Phys. Lett. 111 021101
[32] Cao W, Singh R, Zhang C, Han J, Tonouchi M and Zhang W 2013 Appl. Phys. Lett. 103 101106
[33] He X, Yao Y, Yang X, Lu G, Yang W, Yang Y, Wu F, Yu Z and Jiang J 2018 Opt. Commun. 410 206
[34] Kalhor S et al 2021 Nanomaterials 11 2999
[35] Xu H, Wang X, Chen Z, Li X, He L, Dong Y, Nie G and He Z 2021 New J. Phys. 23 123025
[36] Nakamitsu T and Kitano M 2018 Appl. Phys. Lett. 112 201905
[37] Chen M, Xiao Z, Lu X, Lu F, Cui Z and Xu Q 2020 Opt. Mater. 102 109811
[38] Li D, Ji Z and Luo C 2020 Opt. Mater. 104 109920
[39] Hu Y, Tong M, Hu S, He W and Jiang T 2022 Nanophotonics 11 1367–78
[40] Huang Y, Nakamura K, Takida Y, Minamide H, Hane K and Kanamori Y 2020 Sci. Rep. 10 20807
[41] Kim T-T, Kim H-D, Zhao R, Oh S S, Ha T, Chung D S, Lee Y H, Min B and Zhang S 2018 ACS Photon. 5 1800
[42] Lee S, Baek S, Kim T T, Cho H, Lee S, Kang J H and Min B 2020 Adv. Mater. 32 2000250
[43] Withayachumnankul W and Abbott D 2009 IEEE Photon. J. 1 99
[44] Xu W, Xie L and Ying Y 2017 Nanoscale 9 13864
[45] You X, Ako R T, Lee W S L, Low M X, Bhaskaran M, Sri ram S, Fumeaux C and With ayachumnankul W 2019 Adv. Opt. Mater. 7 1900791
[46] He W, Tong M, Xu Z, Hu Y and Jiang T 2021 Photon. Res. 9 1099
[47] Han S et al 2019 Adv. Mater. 31 1901921
[48] Prasankumar R P, Scopatz A, Hilton D J, Taylor A J, Averitt R D, Zide J M and Gossard A C 2005 Appl. Phys. Lett. 86 201107
[49] Vanderhoef L R, Azad A K, Bomberger C C, Chowdhury D R, Chase D B, Taylor A J, Zide J M and Doty M F 2014 Phys. Rev. B 89 045418
[50] Liu X, Starr T, Starr A F and Padilla W J 2010 Phys. Rev. Lett. 104 207403
[51] Padilla W J, Taylor A J, Highstrete C, Lee M and Averitt R D 2006 Phys. Rev. Lett. 96 107401
[52] Chou Chau Y-F, Chen K-H, Chiang H-P, Lim C M, Huang H J, Lai C-H and Kumara N T R N 2019 Nanomaterials 9 1691
[53] Naftaly M and Miles R E 2007 Opt. Commun. 280 291
[54] Banerjee S, Lok Abhishikth N, Karmakar S, Kumar D, Rane S, Goel S, Azad A K and Roy Chowdhury D 2020 J. Opt. 22 125101