Thermally controlled electromagnetically induced transparency in hybrid metal-InSb metamaterials at THz frequencies

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Abstract. We demonstrate an active controlled electromagnetically induced transparency (EIT) device via thermal control in a hybrid metamaterial, which consists of two split-ring resonators (SRRs) with integrated InSb-metal and a cut wire (CW) in a unit cell. We can dynamically control the amplitude modulation of the EIT window, by varying the temperature of the InSb thereby changing the damping rate of the dark mode of SRRs. When the temperature of the InSb changes from 240K to 320K, the EIT window undergoes modulation from on to off, and the modulation depth reaches 86.8%. The results are not only promising in designing compact slow light devices in the terahertz regime but also leading some essential applications in terahertz communications.

1. Introduction
Terahertz (THz) technology and terahertz functional devices have drawn researchers’ attentions in recent years [1, 2]. However, it is difficult to control and modulate THz waves with dynamically control via varying structure of the metamaterials. Therefore, active control of THz devices has shown a great prospect in terahertz metamaterials [3, 4]. To achieve the purpose of actively controlling THz waves, the main methods are electric control [4], optical control [5], magnetic control [6] and thermal control [7]. Getting rid of electronically controlled external drive circuits and light-controlled lasers, the metamaterials based on thermal control are advantageous to develop a thermal control switch system and study thermodynamics.

Electromagnetically induced transparency (EIT), which is a quantum interference effect that occurs in atomic systems, appears a narrowband transparency window in the spectrum [8]. However, limited materials and strict experimental conditions have greatly restricted further research and practical applications of the EIT effect in atomic systems. Thus, employing metamaterials to mimic the EIT in classical optical systems has received widespread attentions by simulating EIT responses through near-field coupling between bright and dark mode resonators in artificially tailored nanostructures [9].

In this paper, we propose a novel design of metamaterial, composed of the silicon substrate and the InSb integrated metallic structures, which can realize active control of electromagnetically induced transparency (EIT) in terahertz bands. We demonstrate that the EIT resonance can switch from on to off, by changing the external temperature (from 240K to 320K). Analyzing the field distributions of the metamaterial, we also clarify the physical mechanism of active modulation is that the conductivity of the InSb increases the loss of the dark mode. This work provides a useful tool in designing active devices, which will promote the applications of low light devices at THz frequencies.
2. Design and simulation methods
The unit cell of metamaterial as shown in Figure 1 (a) consists of a cut wire (CW) and two split-ring resonators (SRRs), and the InSb is positioned in the gaps of SRRs. Since the resonance between the CW and the SRRs is mainly determined by their geometric size and the period of the subwavelength unit cell, in order to obtain the standard EIT line shape, after many simulations and optimizations, the length and the width of the CW are \( H \) and \( w \), respectively. The base lengths of SRRs are \( L \), and the gaps of the SRRs are \( g \). The distance between CW and SRRs is \( s \). The thickness of the InSb is \( h \). The CW and SRRs are 200-nm-thick aluminum modeled with DC conductivity of \( 3.56 \times 10^7 \, \Omega^{-1} \, \text{m}^{-1} \), and the unit cell is periodically fabricated on the top of a 500-um-thick silicon layer, with permittivity of silicon is 11.7 \([10, 11]\).

![Figure 1. Schematics of the active EIT metamaterial. (a) Schematics of the unit cell. The geometrical parameters are \( \text{P}x = 80 \mu \text{m}, \, \text{P}y = 110 \mu \text{m}, \, H = 86 \mu \text{m}, \, H1 = 500 \mu \text{m}, \, h = 2 \mu \text{m}, \, w = 5 \mu \text{m}, \, s = 8 \mu \text{m}, \, L = 30 \mu \text{m}, \, g = 5 \mu \text{m} \), respectively. (b) Three-dimensional schematic diagram of the proposed structure. The incident electric field is along the y-direction.](image)

Terahertz time-domain spectroscopy (THz-TDS) is used to calculate the transmission spectra and investigate the near-field coupling effect of the hybrid metamaterial under a vacuum environment when the \( y \)-polarized plane wave incidents into the metamaterial. The periodic boundary condition is adopted on the x and y direction, and the perfectly matched layer boundary is employed for the hybrid metamaterial in the z direction. The permittivity of the InSb is \([12]\]

\[
\varepsilon(w) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega \gamma},
\]

where, the \( \varepsilon_\infty = 15.68 \) is the realistic parameters of the InSb and \( \omega \) is the angular frequency of the plane wave. In addition, \( \gamma \) is the damping constant. The plasma frequency \( \omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m^*}} \) is up to the free carrier density \( N \), where \( e \) is the electronic charge, and \( \varepsilon_0, \, m^* \) are the vacuum permittivity and the effective mass, respectively. The intrinsic carrier density \( N \) (in \( \text{m}^{-3} \)) in InSb is \([7, 8]\]

\[
N = 5.76 \times 10^{20} T^{3/2} \exp(-0.26/2k_B T),
\]

where, the \( k_B \) is the Boltzmann constant and the \( T \) is the temperature in Kelvin.

The variation in \( T \) causes the change in \( N \), which also makes the plasma frequency \( \omega_p \) tunable via changing the temperature \( T \). Therefore, \( N \) strongly depends on \( T \), as shown in Figure 2, and we can obtain that the InSb shows dielectric features when the temperature \( T \) changes from 240K to 320K. We can expect that the transmission spectrum for metamaterials comprising InSb dielectric will
change. Since the $N$ highly relies on the environmental temperature, we simulate the situations of the hybrid metamaterial via changing the temperature of the InSb.

![Figure 2](image_url1)  
**Figure 2.** Temperature dependent permittivity of the InSb. (a) The real part of the permittivity. (b) The imaginary part of the permittivity.

3. **Result and discussion**

In order to illustrate that the EIT effect occurs by causing near-field coupling effect in the proposed metamaterial, we calculated the transmission spectra of the CW, SRRs array and the proposed structure, respectively, as shown in Figure 3. Normally, the EIT-like spectral response results from the destruction of the resonance between the bright and dark modes. Bright mode and dark mode have low quality factor and high quality factor, respectively, due to their own characteristics. We can see that the CW and SRRs show typical bright mode and dark mode transmission spectra, respectively, as shown in Figure 3.

![Figure 3](image_url2)  
**Figure 3.** Transmission spectrum of the CW, SRRs and purposed structure, when the temperature of the InSb is 240K with a y-polarized electric field.

The transmission spectra of the metamaterial are calculated for various temperatures ranging from 240K to 320K, as shown in Figure 4. It can be seen that the transmission peak of the proposed metamaterial would experience an on-to-off switching modulation. This is due to the InSb is integrated into the SRRs, the coupling effect would obtain an active modulation via changing the
temperature of the InSb. When the temperature is 240K, we can observe an apparent transparency peak between two resonance dips at 0.665 THz, with the transmission amplitude of 82.89%. The transmission amplitude decreases quickly with the increasing of temperature. When the temperature increases to 320K, the transparency peak disappears with the transmission amplitude of only 5.85%.

The modulation depth of the designed structure is 86.8%, which is defined as $M = \frac{|T_{\text{max}} - T_{\text{min}}|}{(T_{\text{max}} + T_{\text{min}})} \times 100\%$, where $T_{\text{max}}$ and $T_{\text{min}}$ are the transmission rates at an InSb temperature of 240K and 320K, respectively.

![Simulated transmission spectra with varying the temperature of InSb from 240K to 320K.](image)

**Figure 4.** Simulated transmission spectra with varying the temperature of InSb from 240K to 320K.

To clarify the coupling effect of the resonances, the E-field and the H-field distributions of the transparency peaks with the temperature changing are calculated at 0.665 THz, respectively, as shown in Figure 5. From Figures 5(a) and (f), we can obtain that both the electric field and the magnetic field are gathered in SRRs when the temperature is 240K. We infer the dark SRRs have a small damping rate. In other words, the dark resonance modes have a small loss and strong excitation. When the InSb is inserted in SRRs, it can be seen as a conductive dielectric that connects the gaps of the SRRs, and its conductivity would increase as temperature rises. From Figures 5(b) and (g), the energy in the dark mode SRRs is gradually decreasing, and the energy in the CW is increasing at a temperature of 260K. When the temperature is 280K, the electric field and the magnetic field in the SRRs decrease significantly, while the electric field in CW starts to strengthen, as shown in Figures 5(c) and (h). With the temperature up to 320K, the coupling between the bright mode and the dark mode is suppressed, while the electric field and the magnetic field are relocalized in the CW, as shown in Figures 5(e) and (j). This is due to the existence of the InSb that the SRRs are completely connected, which caused the disappearance of the transparency peak.
Figure 5. (a-e) E-field and (f-j) magnetic field distributions of the proposed metamaterial with varying temperatures at the resonance frequency of 0.665 THz.

4. Conclusions

We design an active control metamaterial via integrating the InSb into the THz metamaterial composed of the dark SRRs and the metallic bright CW, which provide the dark mode and bright mode respectively. The coupling effect between the bright and dark modes is controlled by changing the temperature of the InSb placed the SRRs. When the temperature is 240K, the standard EIT line shape is displayed. As the temperature increases, the EIT line shape gradually changes. When the temperature reaches 320K, the EIT line shape disappears, and the modulation depth of the EIT window reaches 86.8%. The thermally active tuning of EIT metamaterial may play a key role in applications, which is helpful in developing active slow devices and nonlinear devices at terahertz frequencies.

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References

[1] Sizov F and Rogalski A 2010 THz detectors Progress in Quantum Electronics 34 278-347
[2] Seeds A J, Shams H, Fice M J and Renaud C C 2015 TeraHertz Photonics for Wireless Communications Journal of Lightwave Technology 33 579-87
[3] Li G, Zhou Q L, Liang W, Zhang C, Zhang X C, Tani M and Zhang C 2019 Reversible composite terahertz modulator based on VO2 phase transition. In: Infrared, Millimeter-Wave, and Terahertz Technologies VI pp 1119616-1
[4] Yin S, Shi X, Huang W, Zhang W, Hu F, Qin Z and Xiong X 2019 Two-Bit Terahertz Encoder Realized by Graphene-Based Metamaterials Electronics 8 1528
[5] Su X, Ouyang C, Xu N, Tan S, Gu J, Tian Z, Han J, Yan F and Zhang W 2015 Broadband Terahertz Transparency in a Switchable Metasurface *IEEE Photonics Journal* 7 1-8

[6] Xia L, Zhang X, Wang D, Zhang W and Han J 2019 Terahertz surface magnetoplasmons modulation with magnetized InSb hole array sheet *Optics Communications* 446 84-7

[7] Wang B X and Wang G Z 2017 Temperature tunable metamaterial absorber at THz frequencies *Journal of Materials Science: Materials in Electronics* 28 8487-93

[8] Gu J, Singh R, Liu X, Zhang X, Ma Y, Zhang S, Maier S A, Tian Z, Azad A K, Chen H T, Taylor A J, Han J and Zhang W 2012 Active control of electromagnetically induced transparency analogue in terahertz metamaterials *Nat Commun* 3 1151

[9] Chen H T, Padilla W J, Zide J M, Gossard A C, Taylor A J and Averitt R D 2006 Active terahertz metamaterial devices *Nature* 444 597-600

[10] Srivastava Y K, Manjappa M, Cong L, Cao W, Al-Naib I, Zhang W and Singh R 2016 Ultrahigh-QFano Resonances in Terahertz Metasurfaces: Strong Influence of Metallic Conductivity at Extremely Low Asymmetry *Advanced Optical Materials* 4 457-63

[11] Lu X, Han J and Zhang W 2011 Localized Plasmonic Properties of Subwavelength Geometries Resonating at Terahertz Frequencies *IEEE Journal of Selected Topics in Quantum Electronics* 17 119-29

[12] Howells S C and Schlie L A 1996 Transient terahertz reflection spectroscopy of undoped InSb from 0.1 to 1.1 THz *Applied Physics Letters* 69 550-2