Plasmon induced transparency effect through alternately coupled resonators in terahertz metamaterial

KOIJAM MONIKA DEVI,1,* AMARENDRA K. SARMA,1 DIBAKAR ROY CHOWDHURY,2 AND GAGAN KUMAR1

1Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India
2Mahindra École Centrale, Jeedimetla, Hyderabad 500043, Telangana, India

*koijam@iitg.ernet.in

Abstract: We analyze plasmon induced transparency (PIT) in a planar terahertz metamaterial comprising of two C-shaped resonators and a cut-wire. The two C-shaped resonators are placed alternately on both sides of the cut-wire such that it exhibits a PIT effect when coupled with the cut wire. We have further shown that the PIT window is modulated by displacing the C-shaped resonators w.r.t. the cut-wire. A lumped element equivalent circuit model is reported to explain the numerical observations for different coupling configurations. The PIT effect is further explored in a metamaterial comprising of a cross like structure and four C-shaped resonators. For this configuration, the PIT effect is studied for the incident light polarized in both x and y directions. It is observed that such a structure exhibits equally strong PIT effects for both the incident polarizations, indicating a polarization independent response to the incident terahertz radiation. Our study could be significant in the development of slow light devices and polarization independent sensing applications.

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References and links
1. Introduction

Metamaterials are artificial engineered materials having unusual electromagnetic properties [1–3]. Research in metamaterials has been gaining momentum over the past decade, owing to its ability in controlling electromagnetic wave properties through careful design [4] at the sub-wavelength scale. Numerous structures such as planar resonators [5, 6], multi-layered structure [7, 8], hole arrays [9, 10], etc. have been studied extensively for various applications. In 2008, a novel study done by Zhang and his co-workers revealed that an electromagnetically induced transparency (EIT) like phenomenon can occur in plasmonic metamaterials [11]. EIT is a quantum interference phenomenon occurring in a three level atomic system. In EIT, an atom that absorbs a particular light is rendered transparent by shining another light having the same resonance frequency [12, 13]. The plasmonic analogue of this EIT effect is known as plasmon induced transparency (PIT) effect in metamaterials [11, 12, 14]. PIT usually occurs as a result of interference between a bright and a dark mode. The bright mode strongly couples with the incident light while the dark mode couples weakly to the incident light [11, 15–18]. Both the modes should have similar resonant frequencies with a very little deviation. In such a situation, the destructive interference of these modes induce a narrow transparency region in the otherwise absorptive spectrum. Within this region all the incident radiation gets transmitted through the medium and the dispersive properties of the medium gets strongly modified.

The PIT effect has been realized in a variety of metamaterial configurations. The planar metamaterial configurations such as metal strips and coupled split ring resonators have been reported to exhibit PIT effect in gigahertz as well as terahertz regime [19–22]. Active control and tuning the transparency window as well as its slow slight properties have also been explored over the recent years [19, 23–25]. The PIT study has also been extended to different materials and exploring their capability in producing such effect. The materials such as silicon and graphene have been found to exhibit interesting PIT properties too [21, 22, 26–28]. The research activities in this area are strongly motivated by the fact that it can lead to the development of sensing [29–33] and slow light devices at room temperature [34 –37]. The experimental investigations in this area have been supported by the well-defined theories such as equivalent circuit [12, 38] and coupled Lorentz oscillator models [11, 19, 23]. In exploring PIT, the studies largely have focused to examine this effect for a specific polarization of the incident light for which the effect is prominent. As we switch to the different polarization, the effect becomes either weaker or completely vanishes. In this context, strategically designed structures in metamaterials have been recently examined that are found to exhibit polarization independent PIT response [39, 40]. Further, the research in this area is motivated for the development of more simplistic designs explaining the effect.

In this article, we analyze a coupled resonator comprising of two C-shaped (2C) resonators and a cut-wire (CW) like structure. The PIT in the proposed model occurs due to the destructive interference between the cut-wire (CW) and the two C-shaped resonators. Although, the displacement of the C-shaped resonators in the y-direction has been studied in earlier works [41, 42], the novelty of our work stems from the investigation of the coupling mechanism in the x-direction which was earlier overlooked. When the C-shaped resonators are displaced in the y-direction, the dark mode excitation in the PIT metamaterial is achieved through both electric and magnetic fields of the CW. As the C-shaped resonator pair is translated along the CW starting from the bottom, the coupling mechanism switches from being capacitive in nature via the electric field to being inductive via the magnetic field of the CW [41]. However, the dark mode is excited only through the electric field of the CW as the C-shaped resonators are translated in the x-direction, resulting in a capacitive coupling between the C-shaped resonator pair and the CW. It is observed
that the transparency window can be broadened by increasing the coupling between the CW and the two C resonators. A simple lumped element equivalent circuit model using coupled oscillator theory is described to confirm the numerical observations. The PIT effect in the proposed geometry occurs only when the incident polarization is parallel to the longitudinal direction of the CW. This may limit the use of PIT effect for development of sensing applications. In order to overcome this, we introduce two C and a CW structure in the perpendicular orientation in our metamaterial geometry so that the new meta-molecule consists of a cross wire and four C (4C) resonators. In order to establish the polarization independent response, we examine PIT effect from this new meta-molecule for the x and y polarized incident radiation. This paper is organized as follows: First we discuss the design and numerical simulations of the PIT with alternately placed C-shaped structures w.r.t. the cut wire. Next, we discuss theoretical model that is used to explain our numerical observations. The polarization independent response of the proposed metamaterial is examined in the subsequent section. The results are summarized in the conclusion section.

2. Plasmon induced transparency: Geometry and numerical simulations

![Fig. 1. (a) Schematic diagram of the planar metamaterial geometry comprising of a cut-wire and two C shaped resonators. (b) Transmission Plot for CW, 2C and the PIT effect for the y-polarized incident light.](image)

The meta-molecule of the proposed structure comprises of a CW and two C shaped resonators and is designed in a way that they can exhibit PIT effect with CW as the bright resonator. The schematic diagram of the proposed metamaterial geometry is shown in Fig. 1(a). In the proposed geometry, the quantity ‘L’ represents the length of the CW, ‘a’ represents the dimension of each of the C shaped resonator, ‘w’ denotes the width of the CW as well as the C resonators and ‘g’ stands for the gap of the C shaped resonators. The periodicity of the meta-molecule is denoted by ‘p’ and is taken to be 140 μm in our simulations. For our simulations, we have taken $L = 84 \ \mu m$, $a = 35 \ \mu m$, $w = 4 \ \mu m$ and $g = 27 \ \mu m$. The distance ‘d’ between the CW and the 2C structures is varied in our numerical simulations to examine modulation response of PIT effect. The CW and the 2C are assumed to be made up of aluminium having thickness, $t = 200 \ \text{nm}$ on a quartz substrate of thickness, $h = 25 \ \mu m$, with a relative permittivity $\epsilon_r = 3.75$. It may be noted that in the simulation model, we have considered dc conductivity to model aluminium. The numerical simulations are performed using the technique of finite element frequency domain solver in CST Microwave Studio. The metamaterial geometry is simulated under the unit cell
boundary conditions in the x-y plane. We set open boundary conditions along the direction of light propagation and chose a mesh size of the order of $\lambda/10$, where $\lambda$ is the wavelength of the incident radiation. The simulation is performed for the y linearly polarized light under the normal incidence.

Figure 1(b) shows the terahertz transmission response through the proposed metamaterial configuration for the y- polarized incident terahertz radiation. The blue traces represent the bright mode while the red traces represent the dark mode. The green traces signify the PIT effect from the proposed terahertz metamaterial geometry. It may be noted that the array of CWs exhibit a typical localized surface plasmon resonance at $f = 1.0$ THz while the two C structures support an LC resonance at the same frequency. It may be noted that the CWs couple directly to the incident light and has a deep transmission dip and broad spectral response. On the other hand, the 2 C structures result in a weakly coupled response to the incident terahertz beam. The resonances from the CWs and 2 C structures behave like a bright mode and dark mode respectively. The interference of these two modes induces a narrow transparency window in the transmission spectrum represented by green traces in the figure. In order to further understand the bright and dark modes as well as the PIT effect, we observe the induced electric field profiles in the transparency region i.e. at 1.0 THz. The results are shown in Fig. 2. We may note that the CW structure gets directly excited by the incident light resulting in a bright mode (Fig. 2(a)), while

![Image of electric field profiles](image)

**Fig. 2.** Electric field profiles of (a) the CW structures, (b) the 2C structures and (c) the proposed PIT metamaterial. The green arrow signifies the direction of electric field of incident polarization.

![Image of transmission versus frequency](image)

**Fig. 3.** Transmission versus frequency for different distances $d'$ of the proposed terahertz metamaterials geometry exhibiting PIT effect. A decrease in the distance $d'$ results in the broadening of the transparency window.
the 2 C shaped resonators are excited indirectly via coupling of the CW resonance resulting in
dark mode (Fig. 2(b)). When these two modes are allowed to couple with each other, a narrow
transparency window is induced due to the destructive interference of the modes (Fig. 2(c)). In
this transparency window, the imaginary part of the field becomes negligible and the structure
becomes highly dispersive. This results in the significant reduction of the velocity of the incident

Next, we examine the displacement of C-shaped resonators w.r.t. the CW which is responsible
for a coupling between the resonator and hence a modulation of transparency window is possible.
This modulation is done by varying distance ‘d’ from 2 µm to 20 µm. The results of transmission
for different values of ‘d’ are shown in Fig. 3. The red traces represent the PIT effect for
\( d = 2 \mu m \), \( d = 10 \mu m \) and \( d = 15 \mu m \) respectively. The orange traces represent the case of \( d = 20 \mu m \) and contribute
to the weakest coupling. It is evident that the PIT window gets narrower as we increase distance
‘d’. The narrowing of the PIT window occurs due to a reduction in the coupling of CW with the
C-shaped resonators. Such a behavior indicates that the PIT effect can be modulated efficiently
by varying the coupling between the bright and the dark modes.

3. Semi-analytical model elaborating PIT effect

![Fig. 4. An equivalent circuit model for the proposed PIT metamaterial shown in Fig. 1(a).](image)

In order to elucidate our numerical findings on plasmon induced transparency as observed in
this work, we use an equivalent RLC circuit model which is shown in Fig. 4. In the model, the
left hand loop consisting of \( R_1, L_1, C_1 \) and the right hand loop consisting of \( R_2, L_2, C_2 \) forms a
resonant circuit having resonance at \( f = 1.0 \) THz. The left hand loop represents the bright mode
or the CW resonator, while the dark or 2 C resonator is represented by the right hand loop. The
capacitance \( C_c \) in the circuit accounts for the coupling between the bright and the dark modes.
The incident terahertz field is represented by \( V(t) \) in the model. The bright mode is directly
excited by the incident terahertz radiation while the dark mode is excited through coupling with
the bright mode. For currents, say \( i_1 \) and \( i_2 \) flowing through the left and the right hand loop, then
following the standard circuit analysis [2, 38], one may write

\[
\begin{pmatrix}
i_1 \\
i_2
\end{pmatrix} = \begin{pmatrix}
\frac{-j\omega L_1 + R_1 + \frac{1}{-j\omega C_1}}{-j\omega C_c} & \frac{1}{-j\omega C_c} \\
\frac{-j\omega L_2 + R_2 + \frac{1}{-j\omega C_2}}{-j\omega C_c} & \frac{-j\omega L_2 + R_2 + \frac{1}{-j\omega C_2}}{-j\omega C_c}
\end{pmatrix}^{-1} \begin{pmatrix} V \\ 0 \end{pmatrix}.
\]

Equation (1) can be transformed into the transmission parameter \( t(\omega) \) using the standard
parameters conversion formula [43]. This gives the transmission coefficient \( t(\omega) \),

\[
t(\omega) = \frac{2Z_{21}\sqrt{R_{01}R_{02}}}{(Z_{11} + Z_{01})(Z_{22} + Z_{02}) - Z_{12}Z_{21}},
\]

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where $Z_{01}$ and $Z_{02}$ are the source and the load impedances of a general two port system. $R_{01}$ and $R_{02}$ are the real parts of $Z_{01}$ and $Z_{02}$.

Using this semi analytical approach, we calculate transmission results corresponding to a specific set of parameters that we used in our numerical simulations of the PIT effect. The transmission is calculated for different values of \(d\) which causes a varying coupling between the CW and the two C-shaped resonators as discussed above. The results are depicted in Fig. 5. It is worthwhile to mention that the provided circuit model uses a capacitive coupling, represented by $C_c$, to explain the PIT response in the proposed metamaterial structure. This coupling could be modulated by varying the value of the capacitance $C_c$ used in the model. As such, this model can be used to predict the near field coupling in metamaterial systems where capacitive coupling is dominant. Hence, we may observe the modulation of the transparency window by varying the value of $C_c$ (Fig. 5). It is evident that the results from semi-analytical approach are in good agreement with the numerical observations of Fig. 3.

![Graph showing transmission results](image)

**Fig. 5.** Transmission plot for the proposed metamaterial structure obtained using the semi-analytical model.

### 4. Polarization independent plasmon induced transparency

In the metamaterials configuration proposed above, the PIT effect occurs only when the incident polarization is parallel to the longitudinal direction of the CW. However, for certain applications, a polarization independent response may be desirable. In order to achieve a polarization independent PIT effect, we introduce two more C and one CW structure in the above design in perpendicular orientation. The schematic of this new meta-molecule now comprising of a cross and four C resonators is shown in Fig. 6 along with the transmission results. We study transmission through this new design for the x and y linearly polarized lights so as to elucidate our impression of polarization independent response. We observe that the design exhibits equally strong PIT effect for both the polarizations which is explained through several steps in Figs. 6(a)-(f). In the figure, green arrow indicates the direction of incident polarization. The red traces signify the transmission for x-polarized light while the blue traces represent the transmission for the y-polarized light. The transmission for the cross structure is shown in Figs. 6(a) and 6(b) while the transmission for the four C structures is represented by Figs. 6(c) and 6(d). The cross structures show a typical localized surface plasmon resonance at $f = 1.0$ THz while the 4C supports an LC resonance at the same frequency i.e. $f = 1.0$ THz. It is clearly observed from the Figs. 6(a)-(d) that the cross structure has a broader and deeper transmission dip than that
of the 4C structures. The resonance from the cross structure is believed to be a bright mode, however the resonance from the C shaped structures is called a dark mode. When these two modes are allowed to couple with each other, a narrow transparency window is induced due to the destructive interference of the modes. Fig. 6(e) and 6(f) represents the PIT effect of the proposed geometry for both the x and y-linearly polarized lights. We notice an equally strong PIT effect for both the incident polarizations which indicates a polarization independent response of the proposed geometry.

Fig. 6. Terahertz transmission through CW structure for the (a) x-polarized and (b) y-polarized incident terahertz. The green arrow indicates the direction of electric field polarization of incident light. (c) and (d) represent the terahertz transmission for the 4C structure for the two polarizations. (e) and (f) correspond to the PIT effect for both the polarizations. The inset in the figures show the corresponding metamaterials geometry.

Further, we examine the induced electric field profiles for the cross structure, the 4C structure and the PIT metamaterial independently (Fig. 7). The incident polarization is parallel to the direction of the green arrow in the figure. Figure 7(a) and 7(b) represent the electric field profiles of the cross structure at \( f = 1.0 \) THz, for x and y linearly polarized incident light respectively. Figure 7(c) and 7(d) represent the electric field profiles of the 4C structure at \( f = 1.0 \) THz, for the x and y linearly polarized incident lights respectively. It may be noted that for each of the incident polarizations, only the cut wire of the cross structure that is parallel to the incident light is excited, while for the C-shaped resonators whose gap is perpendicular to the incident polarization direction does not get excited in case of 4C structure. When the modes from these excitations are allowed to couple with each other, a narrow transparency window is induced due to the destructive interference of the modes. Figure 7(e) and 7(f) represent the electric field profiles of the PIT effect corresponding to this metamaterial geometry at the PIT transmission peak frequency of \( f = 1.0 \) THz.

Finally, we explore the possibility of modulating the PIT window through this proposed terahertz metamaterial configuration. For doing so, we examine the polarization independent PIT response for different values of \( d' \) for both x and y-linearly polarized incident terahertz light. A change in the value of \( d' \) results in the diagonal shifting of C-shaped resonators w.r.t. the cross wire. The results are shown in Fig. 8. Figure 8(a) represents the transmission for the x-polarized incident light while the transmission response for the y-polarized light is shown in Fig. 8(b). It is evident from the figure that the PIT effect is equally strong for both the x- and y-incident
polarizations. It may be further observed that the transparency window can be modulated by changing the coupling between the cross wire and the C shaped structure through the variation of $d'$. The traces in different colors in the figure represent the transmission response for different values of $d'$ as labeled in the figure itself. The red traces for $d = 2 \mu m$ show the widest, while orange traces for $d = 20 \mu m$ depict the narrowest transparency window. A reduction in the transparency window observed is due to the decrease in coupling as $d'$ increases. The efficient modulation of the PIT window suggests the prospect of developing devices operating within the broad transparency region in terahertz domain. Also, the polarization independent behavior could be significant in the improvement of sensing devices.

Fig. 7. Absolute value of electric field profile for cross structure for (a) x-polarized and (b) y-polarized light at the resonance frequency $f = 1.0$ THz. Electric field profile for 4C structure for (c) x-polarized and (d) y-polarized light at the resonance frequency $f = 1.0$ THz. Electric field profile for the PIT metamaterial structure at the PIT dip for the x-polarized and y-polarized light are depicted in (e) and (f). The incident electric field is parallel to the direction of the green arrow.

Fig. 8. Transmission for a metamaterial comprising of a cross and 4C resonators: (a) x-polarized light and (b) y-polarized light for different values of $d'$. 
5. Conclusions

We have numerically and theoretically analyzed coupled terahertz metamaterials comprising of two C-shaped resonators and a cut-wire (CW) structure. The PIT in the proposed configuration occurs due to the destructive interference of the resonances from the cut-wire (CW) and the two C-shaped resonators. It is observed that the transparency window can be broadened by increasing the coupling between the CW and 2C structures. A simple equivalent circuit model using coupled oscillator theory is described to validate our numerical observations. We extend our analysis to the terahertz metamaterials configuration that comprises of a cross wire and four C-shaped (4C) resonators in order to achieve polarization independent response. Therefore PIT response of this geometry is examined for the two orthogonal polarizations of the incident terahertz beam. The identical transmission response indicates a polarization independent PIT behavior. In this geometry, the transparency window is modulated by displacing the C-shaped resonators diagonally w.r.t. the cross-wire. As the resonators are displaced away from the cross wire, the transparency window gets narrower due to a decrease in the coupling strength. The proposed study could be significant in the realization of terahertz devices such as tunable switches, modulators and slow light systems.

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