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طراحی فراماده جدید و کاربرد آن در تولید نور کند در محدوده تراهرتز

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۱-فارس، شیراز، دانشگاه شیراز، بخش فیزیک، ۸۴۷۹۵-۷۱۹۴۶

چکیده - در این مقاله، ما یک فراماده مسطح جدید پیشنهاد میدهیم که در ساختار آن H-شکل هایی با دو اندازه مختلف وجود دارد که بصورت تو در تو قرار گرفته اند و از جنس مس میباشند. این ساختار روی یک بستر نازک از جنس سیلیکون قرار گرفته است. هرکدام از این دو نوع H با اندازه های مختلف توسط نور فرودی برانگیخته شده و دو مود روشن تولید میکنند. در اثر برهمکنش این دو مود، تداخل کوانتومی ویرانگر رخ داده و پدیده شفافیت القایی پلاسمونیکی (PIT) در محدوده فرکانس های تراهرتز، تولید میشود. این پدیده باعث تولید نور کند شده و سرعت نور را تا ۳۱۰۰ برابر کاهش میدهد. به عبارت دیگر این ساختار گزینه مناسبی برای تولید نور کند بوده و کاربردهای زیادی در طراحی ادوات نور کند، بافرهای نوری و خطوط تاخیر خواهد داشت.

کلید واژه- تراهرتز، شفافیت القایی پلاسمونیکی، فراماده، نور کند.

A Novel Planar Metamaterial Device for Slow Light Application in Terahertz Regime

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Abstract- In this paper, we proposed a novel planar metamaterial which consists of two H-shape structuresof different size which are nested together and are made of Copper deposited on a thin Silicon substrate. The two H-shape structures serve as the bright modes and are exited strongly by the incident wave and interact with each other. This coupling leads to quantum destructive interference and produce plasmonically induced transparency (PIT) effect at terahertz frequencies. This scheme provides a way to achieve slow light and the corresponding group index can reach 3100. Therefore the proposed structure will be useful in designing slow-light devices, optical buffers and delay lines

Keywords: Electromagnetically Induced Transparency, Metamaterial, Slow light, Terahertz

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A Novel Planar Metamaterial Device for Slow Light Applications in Terahertz Regime

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1. Introduction

Slow light, i.e. optical signal propagation at a velocity much slower than the speed of light in the vacuum, has attracted unprecedented attention in the past few years. Using slow light to produce a variable optical delay has important applications for optical signal processing and communication systems, such as optical buffers in advanced optical networks [1], optical memories [2], nonlinear optics [3], and active plasmonic switches [4]. Many researchers have shown how to control over the propagation velocity of light pulses through ultra-cold atomic gases [5], Coherent population oscillation (CPO) [6], Stimulated Raman Scattering (SRR) [7], Stimulated Brillouin Scattering (SBS) [8], Electromagnetically Induced Transparency (EIT) [9], etc.

Among these schemes, EIT is one of the most important approaches which is a quantum destructive interference phenomenon. This destructive interference reveals in elimination of the effect of medium on the propagation of electromagnetic radiation, such that otherwise opaque medium becomes transparent. EIT was demonstrated in a variety of optical systems including coupled resonators, photonic crystals, plasmonic structures, etc. Among them, plasmonic structures based on metamaterials have recently attracted great attention since metamaterials can be designed to mimic various quantum phenomena [10]. Unlike in atomic systems it can be tuned simply by adjusting its geometry and is observed at room temperature. In the optical metamaterial, the mechanism responsible for EIT is quantum interference between different excitation pathways that referred to as Plasmonically Induced Transparency (PIT).

We show in this paper, creation of PIT effect in our structure can lead to reduce velocity of light which has good applications in slow light devices.

2. Structure Description

The metamaterial we proposed is illustrated in Figure 1. The unit cell with a dimension of $P \times P$is composed of fractal H structure containing two different sizes is suitable to mimic EIT.

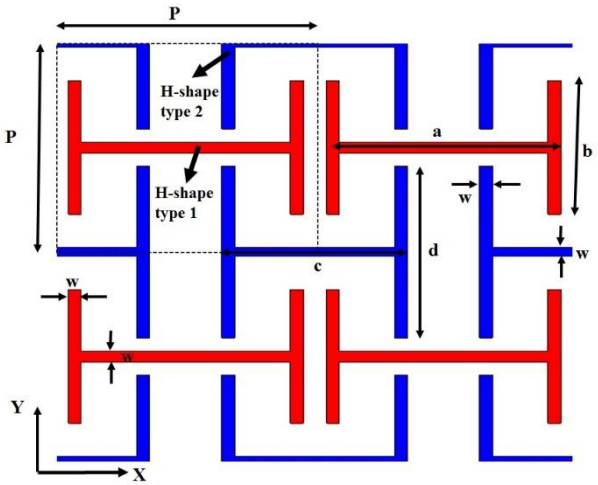


Figure 1: Schematic illustration of the plasmonic metamaterial.

Planar fractal H structure of 2μm thick Copper metal with a conductivity of $6 \times 10^7\ {}^{S}/_{m}$ is placed on a Silicon ($\varepsilon = 11.96$) plate substrate with $5\mu m$ thickness and is located in the $x - y$ plane.

In Figure 1, there are two fractal H structures having different dimensions. Dimensions of H-shape type 1 (H-shape with red colour in Figure 1) are $a = 180\mu m,\quad b = 127\mu m$ and $w = 10\mu m$. The dimensions of the H-shape type 2 (H-shape with blue colour in Figure 1) are $c = 145\mu m, d = 165\mu m$ and$w = 10\mu m$. The periodicity $P = 200\mu m$. A plane wave is incident along the Z-direction with the E_yPolarization. Numerical simulation was performed using a frequency domain solver of 3D electromagnetic package (CST Microwave Studio) and we used periodic boundary conditions (PBC) to truncate the unit cell in the x-y plane.

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3. Creation of PIT Phenomenon

The simulated transmission of H-shape type 1 and H-shape type 2 alone are demonstrated in Figure 2, by dashed and dotted curves respectively. This figure shows a strong plasmon resonance at **I** (0.228 THz) and **III** (0.272 THz) for H-shape structures type 1 and H-shape structure type 2 respectively. These resonances (bright modes) originate from direct coupling of each type H-shape structures alone with the incident electric field. Solid curve in Figure 2, shows that if two H-shape structures are combined, an EIT-like effect transmission window is thus stablished between the bright resonances, while no dark resonator was used in the structure. This transparency window with over 57% transmission at **II** (0.254THz) is observed.

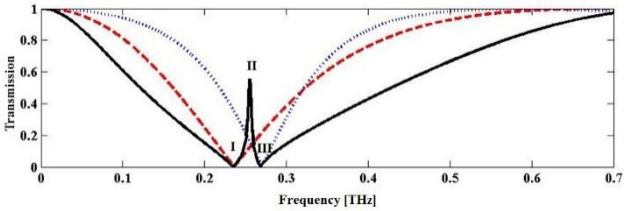


Figure 2: Simulated transmission of H-shape type 1 alone (dashed), H-shape type 2 alone (dotted) and total structure (solid).

In order to insight the physical mechanism behind the EIT-like effect in proposed metamaterial the electric field in the plane of fractal H-shape structures are shown in Figure 3a-c.

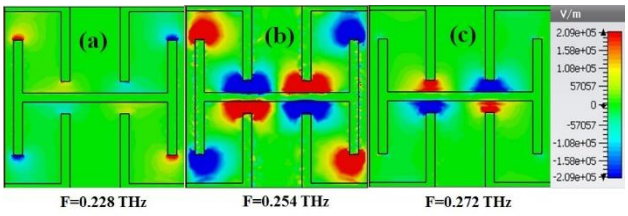


Figure 3: Electric field distribution of metamaterial at different frequencies **I**, **II** and **III** indicate plasmon resonances at 0.228THz, 0.254THz and 0.272 THz.

It is observed from Figure 3a for plasmon resonance **I** that a quadruple moment is created that plays the role of the bright mode and H-shape type 1contribute more in coupling with incident light at this frequency. Plasmon resonance **III** is observed for H-shape type 2 structure and is shown in Figure 3c. Both of the resonances of **I** and **III** serve as bright modes. But at resonance **II**(Figure 3b) the two H-shape structures equally contribute to the resonance and two bright modes couple strongly and an EIT-like effect is induced.

4. Slow Light Devices

Observation of EIT-like effect is very powerful to achieve strong dispersion and highly confined slow light device with a high group index.

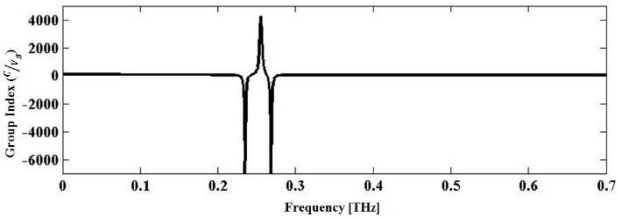


Figure 4: Simulated group delay for proposed metamaterial

We have calculated the group delay by making use of the following equation

$$n_g = \frac{c}{v_g} = n + \omega \frac{dn}{d\omega} \qquad (1)$$

where n_g, c, v_g and n refer to the group index, group velocity of light in vacuum, group velocity of light in metamaterial and effective refractive index respectively.

Figure 4, shows the numerically calculated group index for proposed metamaterial which shows that a group delay exceeding 70 ps and a group index of 3100 is observed. This result is extremely good in comparison with the latest results [11, 12]. Thus this metamaterial structure has potential applications for slow electromagnetic wave velocity.

5. Conclusions

In conclusion, we numerically investigated the phenomenon of PIT in a new metamaterial structure consisting of two H structures whichare nested together. We found that in this metamaterial, an EIT-like effect occurred through bright-bright mode coupling. We could show occurrence of this phenomenonby electric field distribution. In addition, a group velocity of $0.0003\ c$ was obtained in our structure. Therefore, our metamaterial can trap photons for a longer time and enhances light-matter interaction and has the potential application in slow-light and filtering devices.

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