Classical Electromagnetically Induced Transparency in Metamaterials

Vojislav Milošević, Branka Jokanović, Radovan Bojanić and Brana Jelenković

Abstract – **Electromagnetically induced transparency (EIT) is a quantum mechanical phenomenon that creates a narrow transparency window in otherwise absorbing medium. An analogous classical effect can be observed in various systems due to resonators coupling. In this paper, we present a review of metamaterials employing this feature in order to achieve low losses, high dispersion and extreme values of group delay.**

Keywords – **Metamaterials, Electromagnetically Induced Transparency (EIT).**

I. Introduction

In laser physics, EIT has been known as a method to eliminate the effect of the medium on a propagating beam [1]. Typically, it involves three-level atomic system (so called Λ-configuration, depicted in Fig. 1), where the transition between states $|1\rangle$ and $|3\rangle$ is dipole-forbidden (i.e. state $|3\rangle$ is meta-stable). Then, two lasers, probe beam and a considerably stronger pump beam, are tuned to the transitions $|1\rangle \rightarrow |2\rangle$ and $|1\rangle \rightarrow |3\rangle$, respectively. If proper coherence is achieved, it can result in vanishing probability for electrons to be found in the excited state due to quantum mechanical interference, and therefore the probe beam can propagate without any absorption. Classically, the resulting effect can be explained as a consequence of two driving forces acting on electrons, having equal magnitude and opposite sign [1].

Electromagnetically induced transparency is not restricted to quantum mechanics and can be observed in classical mechanical, electrical and plasmonic systems. Classical EIT relies on asymmetrically coupled resonators in respect to the external field. One of the resonators is weakly coupled and is called "dark" element, while the other is strongly coupled and is called "bright" element. To obtain the EIT effects, it is necessary that the "dark" resonator has a considerably greater Q-factor in respect to the "bright" resonator.

In the case of metamaterials consisting from coupled electromagnetic microresonators, this effect results in a sharp transmission peak appearing within wider absorption band [2-7]. This results in a very steep dispersion, which in turn creates very high value of group delay, i.e. very small value of group velocity. It was observed more than 200 times slower wave propagation in metamaterials than the velocity of light in free space, making this type of material suitable for slow-wave applications in terahertz region, [2,3], and for delay-lines in microwave region [7]. Also, due to high Q-factor and strong field confinement, the EIT-like resonance is very sensitive to refractive index of surrounding medium, making it desirable for refractive index-based sensors.

The authors are with the Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia. E-mail: vojislav@ipb.ac.rs

This paper is organized as follows. First, we present the coupled oscillators model that allows us to study the classical EIT phenomenologically. Then, we present a review of recent papers that demonstrate the EIT-like effects in metamaterials.

II. Coupled Oscillators Model

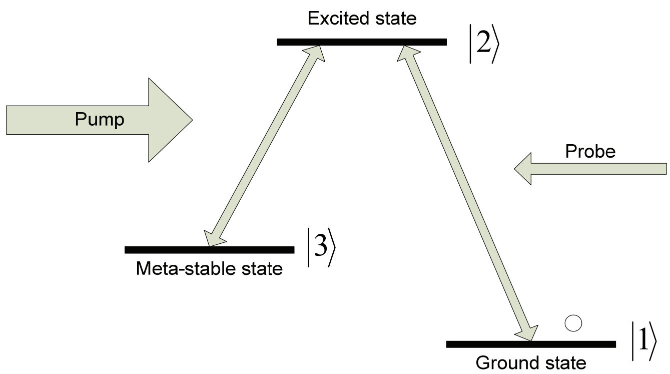


Fig. 1. Typical EIT configuration

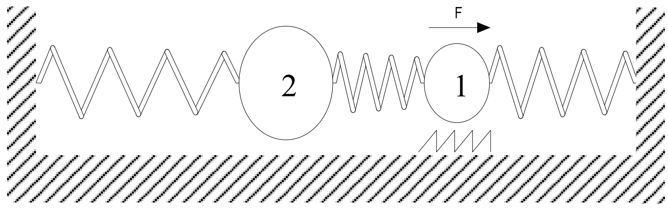


Fig. 2. Coupled mechanical oscillators

In Fig. 2 system of two coupled mechanical oscillators is shown, which we will use to explain the underlying mechanism of classical EIT. Suppose that the particles labelled as 1 and 2 have masses m_1 and m_2, respectively. Both oscillators, when uncoupled (i.e. without the spring in the middle), have the same resonant frequency ω_0, while the damping term associated with particle 2 is considerably smaller than that associated with particle 1, $\gamma_2 << \gamma_1$. Coupling coefficient is denoted as κ. Then, if external time-harmonic force is acting on the particle 1, $F = F_0 e^{j\omega t}$, we can write the following equations of motion ($x_{1,2}$ represent displacements of the respective particles from their equilibrium positions):

$$\frac{\partial^2 x_1}{\partial t^2} + \gamma_1 \frac{\partial x_1}{\partial t} + \omega_0^2 x_1 + \kappa x_2 = F = F_0 e^{j\omega t} \quad (1)$$

$$\frac{\partial^2 x_2}{\partial t^2} + \gamma_2 \frac{\partial x_2}{\partial t} + \omega_0^2 x_2 + \kappa x_1 = 0 \quad (2)$$

In this analogy, force F represents the incoming wave whose transmission is measured (i.e. probe beam), particle 1 represents the electrons, and particle 2 stands for the coupling to the pump beam. If there is movement of particle 1, there is some transfer of energy from the wave, which results in absorption. Therefore, the absorption will be absent in the case when particle 1 stands still.

By solving the system of equations (1), (2) in frequency domain, we obtain the following expression for the displacement of the first particle (as a function of frequency and amplitude of the external force):

$$x_1 = \frac{\left(\omega_0^2 - \omega^2 + j\omega\gamma_2\right)F_0}{\kappa^2 + \left(\omega_0^2 - \omega^2 + j\omega\gamma_1\right)\left(\omega_0^2 - \omega^2 + j\omega\gamma_2\right)} \quad (3)$$

It is apparent from (3) that at the frequency of the resonance ω_0 displacement of the first particle will be proportional to the damping term of the second oscillator, γ_2, which is assumed to be very small, therefore the absorption will be very small too. In the limiting case, when $\gamma_2 \to 0$, it is obvious that x_2 also tends to zero, therefore the absorption of the system is fully removed.

III. Review of Published Papers

One of the first attempts to explore the analogy between the EIT and resonators coupling in metamaterials was done by Tassin *et al.* in [2]. The geometry that was used is depicted in Fig. 3. In the first case (Fig. 3a), the excitation is by the electric field, and symmetrical gaps in the larger split ring have the purpose of preventing it from the coupling with incident field directly, therefore representing “dark” resonator, while the smaller one acts as “bright” resonator. In second case (Fig. 3b) excitation is by magnetic field, and orthogonal ring placement allows only one of them to couple with incident field directly. Dielectrics with different loss tangents have been inserted in the gaps to achieve different Q factors in order to obtain EIT like features.

The results for transmission, absorption and extracted effective permeability for the structure in Fig. 3b is shown in Fig. 4 (both cases from Fig. 3 have similar basic features and therefore we are showing only one). It can be seen that, for strong coupling (blue lines) two clearly separated resonances exist. However, for weaker coupling (red lines) there is narrow transmission window in which Lorentzian shaped absorption curve appears. This strong dispersion in transmission spectrum translates into dispersion in retrieved permittivity in the case of electric coupling with external field (Fig. 3a), and in permeability in the case of magnetic coupling (Fig. 3b). The group index of refraction obtained is about 100, with the losses simultaneously being very small (which can be seen from the imaginary part of refractive index) [2].

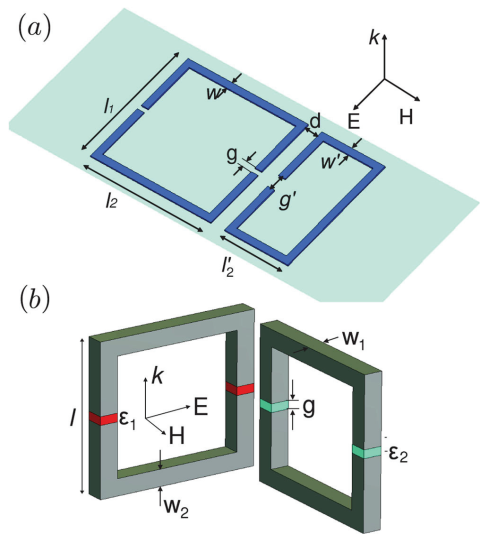


Fig. 3. EIT metamaterial (a) electrically (b) magnetically coupled to the external field [2]

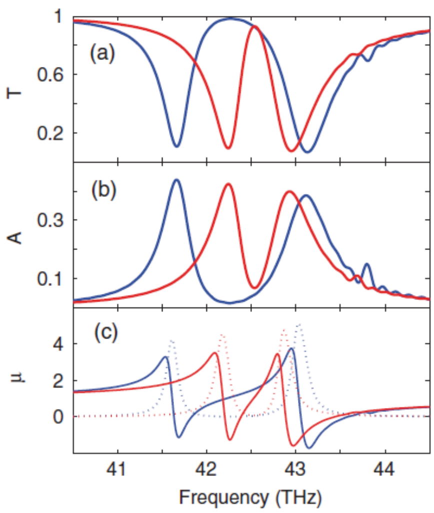


Fig. 4. Results for (a) transmission, (b) absorption and (c) extracted effective permeability for metamaterial in Fig. 3b [2]

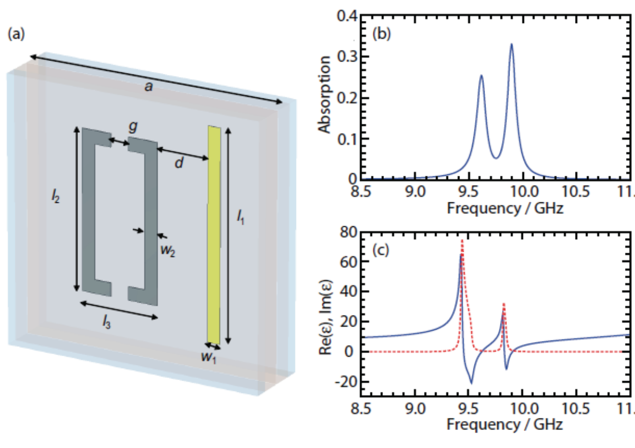


Fig. 5. (a) EIT metamaterial using wire and SRR; (b) absorption spectrum; (c) extracted effective permittivity [3]

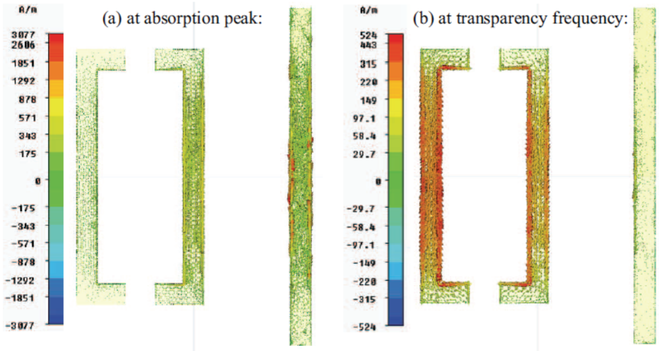


Fig. 6. Current distributions for metamaterial shown in Fig. 5a at (a) absorption peak; (b) transparency frequency [3]

In a subsequent paper from the same group [3] a slightly different approach is used to achieve the EIT-like effect: instead of using different dielectrics to achieve the needed loss contrast between the resonators, two different structures are used. Radiative or “bright” resonator is represented by cut-wire oriented in the direction of the external electric field, while the “dark” resonator is SRR with two symmetric gaps, which doesn’t couple to the external field. It was demonstrated experimentally that the SRR has significantly higher Q-factor than the wire, therefore enabling the EIT-like effect.

The absorption is calculated according to formula $A = 1 - |S_{11}|^2 - |S_{21}|^2$, and it is plotted in Fig. 5b, and the extracted effective permittivity is plotted in Fig. 5c. Again, transparency window is obtained within a wider absorption peak, accompanied by strong dispersion and low losses (imaginary part of permittivity).

The current distributions in resonators have also been calculated for two characteristic frequencies – of peak absorption and transparency, and they are shown in Fig. 6. We can see that at peak absorption, wire is strongly excited, while the current in SRR is small. In the other hand, at transparency frequency, SRR has strong current, while the wire is practically unexcited. This behavior is in a full agreement with that (?) what is expected in the case of EIT [3].

Similar structure is reported in [4], only this time two SRRs, symmetrically placed at both sides of the wire are used instead of one. The sample of this metamaterial was fabricated and measured using X-band waveguide [4].

The examples of classical EIT discussed above use resonators built from metals (e.g. copper), and therefore the difference in Q-factors between bright and dark resonators that can be achieved is about one order of magnitude. To fully pronounce EIT-like effects, Kurter *et al.* in [5] suggested a hybrid metal/superconductor metamaterial. It uses similar geometry as in [4] and [3], with cut wire made of gold, while two symmetrically placed SRRs made of superconductive Nb film. When cooled below its critical temperature, Nb film surface resistance in microwave range becomes very small, providing extremely high Q-factor for the rings.

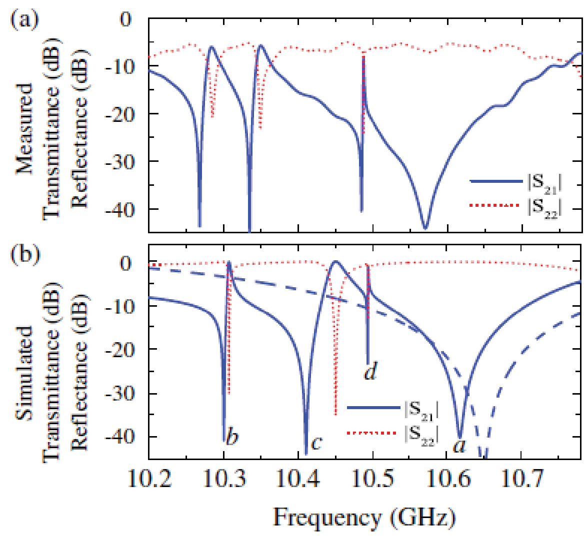


Fig. 7. (a) Measured and (b) simulated transmission and reflection spectrum for the hybrid metal/superconductor EIT metamaterial [5]

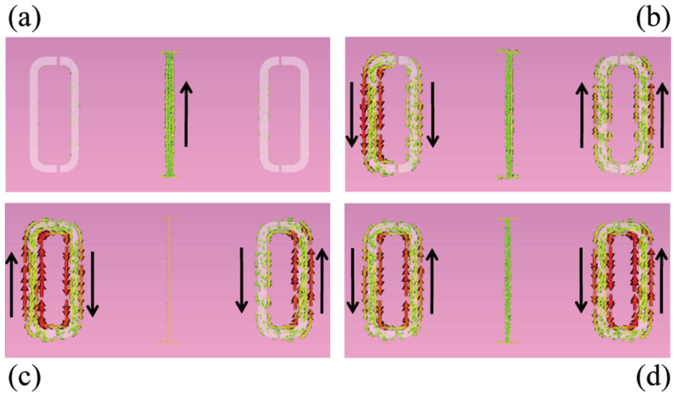


Fig. 8. Current distribution at the characteristic frequencies from Fig. 7a for hybrid metal/superconductor EIT metamaterial [5]

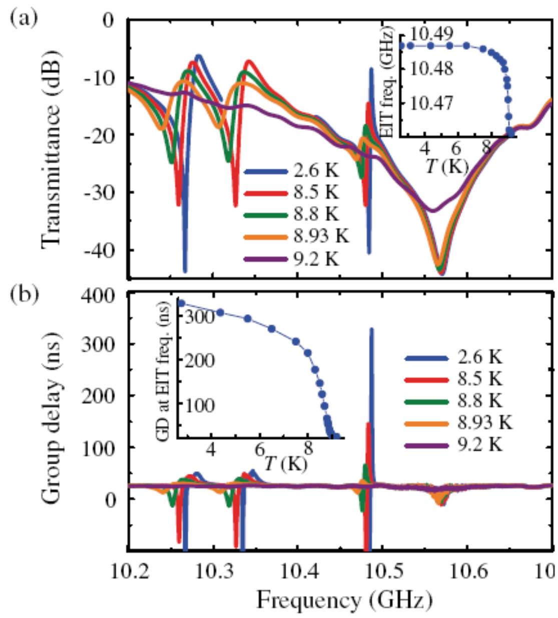


Fig. 9. Control of the group delay by temperature for hybrid metal/superconductor EIT metamaterial [5]

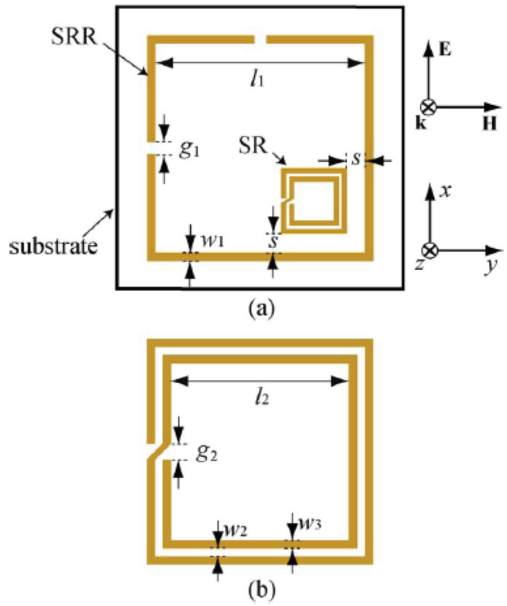


Fig. 10. Polarization independent EIT metamaterial unit cell [6]

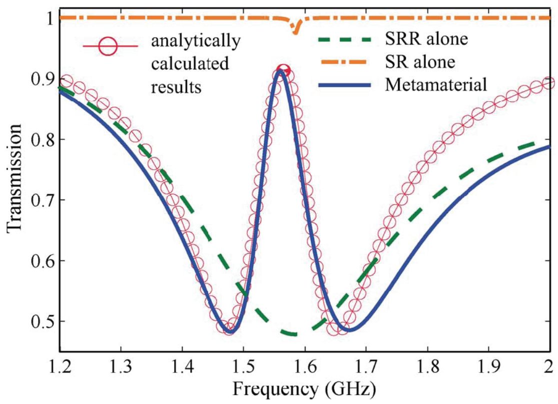


Fig. 11. Simulated transmission through metamaterial consisting only from SRRs, spirals, and both of them combined [6]

Measurement results for transmission in X-band waveguide with inserted unit cell of this metamaterial are shown in Fig. 7. A very interesting fact which can be noted on the plots is that transmission spectrum exhibits three EIT-like features (compared to one in all previous reports). Study of current distributions (see Fig. 8) provides insight into nature of these resonances. Fig 8a shows currents at the maximum absorption frequency, which coincides with dipole resonance of the wire. As it is expected, only the wire is excited, while the rings show? support current at all. Next, in Figs. 8b-d current distributions are shown at the frequencies that correspond to three EIT-like features in Fig. 7 (marked with corresponding letters on plot). It can be seen that the first feature (Fig. 8b) is related with electric dipole resonance of the rings, since both currents flow in the same direction. Other two features (Figs. 8c and d) correspond to symmetric and anti-symmetric normal modes of coupled magnetic resonances of the rings. In previous reports only one EIT-like feature appeared, probably because of the insufficiently high Q-factor of the dark resonator. The authors have also demonstrated the ability to tune EIT-like effect and consequent group delay by controlling the temperature (Fig 9).

All the metamaterials discussed so far exhibit EIT-like effects for a strictly defined linear polarization of incoming radiation, which can be a problem for a number of potential applications where polarization is not *a priori* defined. In an attempt to fix this issue, Meng *et al.* proposed metamaterial unit cell exhibiting EIT-like response for arbitrary (although linear) polarization, intended to be used as a refractive index based sensor [6].

The proposed geometry is shown in Fig. 10. It involves SRR as a bright element, with gaps at two orthogonal sides, therefore producing considerable dipole moment in both x and y directions. Because of this, it will couple to arbitrarily polarized electric field lying in the same plane. The dark element is spiral resonator, which produces negligible electric dipole moment and therefore is uncoupled with the external field. It can be excited, however, with the magnetic field perpendicular to its plane, which is produced by the currents flowing around the SRR, so the two resonators are coupled in this way. It was shown that, due to larger capacitance, the quality factor of the spiral resonator is much larger than that of the SRR (99.8 vs. 8.8).

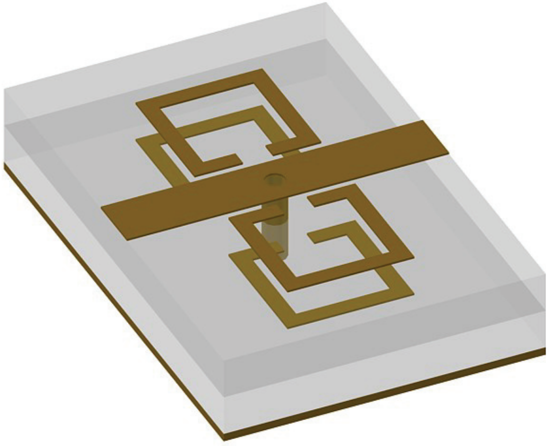
Simulated transmission through metamaterial consisting only from SRRs, spirals, and both of them combined is plotted in Fig. 11. It can be seen that SRR produces wide Lorentzian-like absorption dip, while the spiral practically does not affect the transmission. When they are combined, though, a sharp transmission peak appears, again demonstrating the classical EIT effect. Current distribution analysis shows that the SRR is virtually unexcited at this frequency [6]. Authors analysed the change of the resonant wavelength with the change of refractive index of surrounding medium, and found it to be equal to 77.25mm per unit change of refractive index, thus making this material suitable for sensing applications.

IV. EIT Excited by Planar Transmission Line

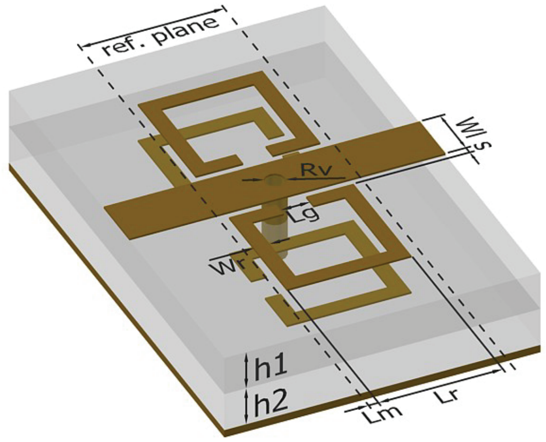
In previously mentioned reports EIT metamaterials are excited either by plane waves or by a waveguide. The authors of this paper, however, proposed the transmission line EIT metamaterial, with the unit cell shown in Fig. 12b [7]. The difference in respect to the standardly used structure, shown in Fig. 12a, is that the SRRs in the middle layer are rotated by 90 degrees. Breaking the symmetry of the resonator in respect to the line result in a different coupling and consequently to considerable slowdown of the propagation field.

The simulated transmission is shown in Fig. 13 and it exhibits an EIT-like feature (shaded on the plot). To further establish this analogy, we extracted index of refraction for the standard transmission line metamaterial (SRRs with all gaps near the line) and for our EIT unit cell. Then we calculated group index according to the expression $n_g = n + \omega\left(\partial n/\partial \omega\right)$, and the obtained results are shown in Figs. 14-15 for the standard SRR arrangement and for the case with twisted SRRs, respectively.

It can be seen from the Figs. 14-15 that transmission line EIT metamaterial exhibits by the order of magnitude larger values of group index (222 vs. 25), which corroborates the aforementioned analogy.



(a)



(b)

Fig. 12. (a) Standard transmission line metamaterial (b) the proposed transmission line EIT metamaterial with relevant dimensions h_1=0.635mm, h_2=1.575mm, ε_{r1}=10.2, ε_{r2}=2.2, L_r=3.15mm, L_m=0.25mm, L_g=0.75mm, S=0.2mm, W_1=1.4mm, W_2=0.4mm, W_3=0.5mm

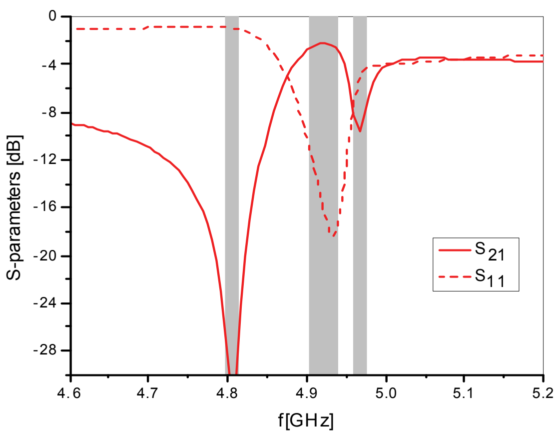


Fig. 13. Simulated *S*-parameters for metamaterial in Fig. 12. Rectangular bar denote characteristic frequencies in EIT response

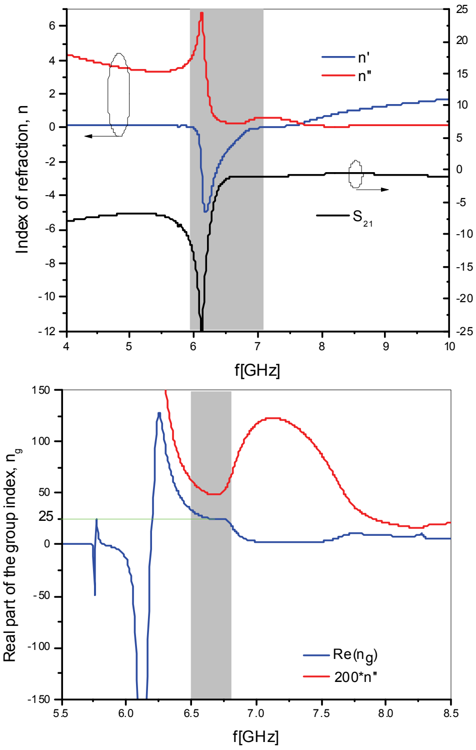


Fig. 14. Index of refraction (a) and group index (b) for the standard transmission line metamaterial with SRRs symmetrically coupled with transmission line

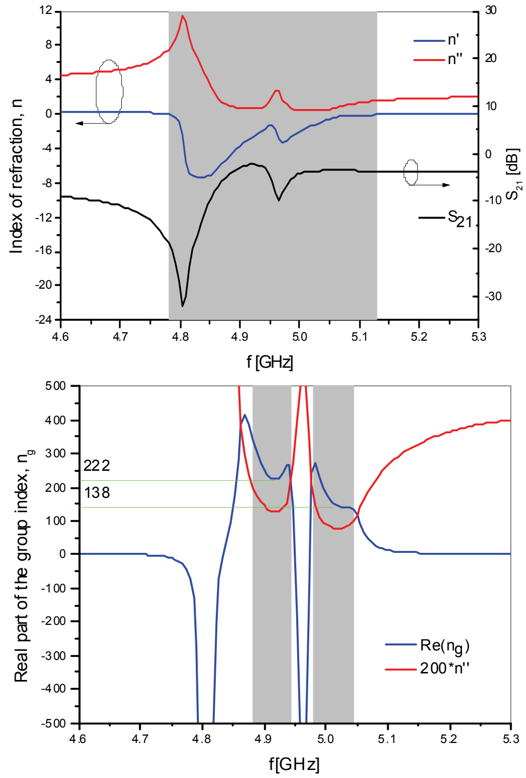
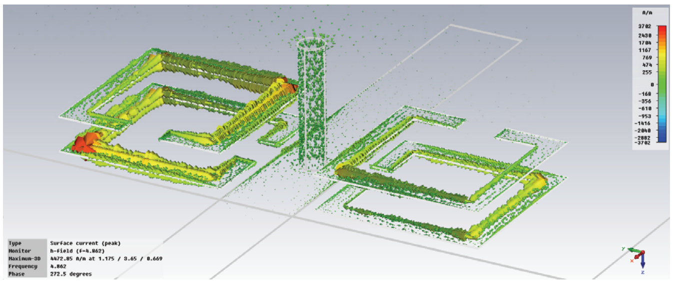
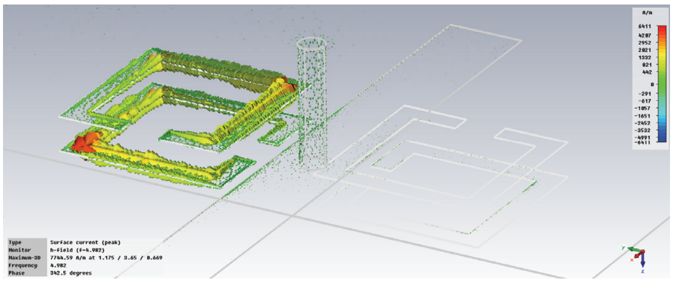


Fig. 15. Index of refraction (a) and group index (b) for the EIT-like transmission line metamaterial

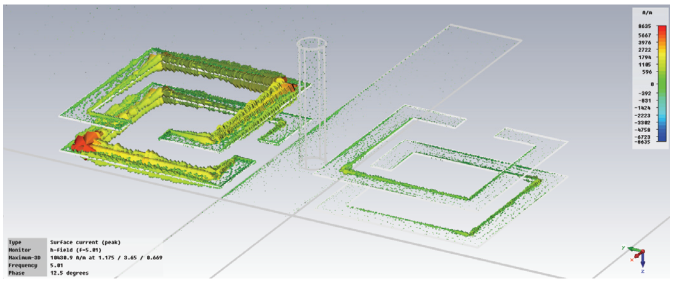
To provide additional insight, we calculated the current distribution at the EIT-like feature frequency, and the results are shown in Fig. 16. It can be seen that at the first characteristic frequency (Fig. 16a) all SRRs and via are excited simultaneously, while at the EIT frequency (Fig. 16b) two pairs of SRRs are excited out of phase and via is almost unexcited. It means that pair of SRRs acting as a "dark" element and since via is virtually unexcited it acts as a "bright" element. It should be noted that current in SRRs, at the different sides of the line, are in the same direction at the first characteristic frequency while there are opposite at the third characteristic frequency.



(a)



(b)



(c)

Fig. 16. Current distribution at EIT-like response at characteristic frequencies denoted in Fig. 13

V. Conclusion

In this paper EIT-like effects in metamaterials were presented, based on an analogy with laser physics. Model consisting of two coupled linear harmonic oscillators was studied in order to gain understanding of the underlying mechanism.

A review of the published literature on this topic was given, including our work on transmission line EIT metamaterials. Common features shared by all the examples discussed include: narrow transmission peak within wider absorption curve, low losses, strong dispersion accompanied by high values of group delay and group index of refraction. These properties make these materials suitable for various applications like slow light, delay lines and sensors.

Acknowledgement

This work has been supported by Serbian Ministry of Education, Science and Technological Development through projects TR-32024 and III-45016.

References

[1] S. Harris, "Electromagnetically Induced Transparency", *Physics Today*, vol. 50, no. 7, pp. 36-42, 1997.

[2] P. Tassin, L. Zhang, Th. Koschny, E. N. Economou, and C. M. Soukoulis, "Low-Loss Metamaterials Based on Classical Electromagnetically Induced Transparency", *Phys. Rev. Lett.*, vol. 102, pp. 053901, 2009

[3] P. Tassin, L. Zhang, Th. Koschny, E. N. Economou, and C. M. Soukoulis, "Planar designs for electromagnetically induced transparency in metamaterials", *Optics Express*, vol. 17, no. 7, pp. 5595-5605, 2009.

[4] L. Zhang, P. Tassin, Th. Koschny, C. Kurter, S.M. Anlage, and C. M. Soukoulis, "Large group delay in a microwave metamaterial analog of electromagnetically induced transparency", *Appl. Phys. Lett.*, vol. 97, pp. 241904, 2010.

[5] C. Kurter, P. Tassin, L. Zhang, Th. Koschny, A.P. Zhuravel, A.V. Ustinov, S.M. Anlage, and C.M. Soukoulis, "Classical Analogue of Electromagnetically Induced Transparency with a Metal-Superconductor Hybrid Metamaterial", *Phys. Rev. Lett.*, vol. 107, pp. 043901, 2011.

[6] F.-Y. Meng, Q. Wu, D. Erni, K. Wu, and J.-C. Lee, "Polarization-Independent Metamaterial Analog of Electromagnetically Induced Transparency for a Refractive-Index-Based Sensor, *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 10, pp. 3013-3022, 2012.

[7] B. Jokanovic, V. Milosevic, R. Bojanic, and B. Jelenkovic, "Theoretical and Experimental Investigations of Reconfigurable Metamaterials Based on Split-Ring Resonators", *3rd Mediterranean Conference on Nanophotonics MediNano-3 - Book of Abstracts,* pp. 26, Belgrade, Serbia, 18-19 October 2010.