Bulletin of Pure and Applied Sciences.
Vol.39 D (Physics), No.2,
July-December 2020 P.186-190
Original Research Article

Print version ISSN 0970 6569
Online version ISSN 2320 3218
DOI: 10.5958/2320-3218.2020.00028.7
Available online at www.bpasjournals.com

Electromagnetically Induced Transparency Effect for Two Level Ensemble Using Multi Mode-Silicon Waveguide Coupled to Plasmonic Resonator Array

Jitendra Kumar Paswan, Sippy Kumari*

Author's Affiliations:

Jitendra Kumar Paswan Research Scholar, University Department of Physics, B.R.A. Bihar University, Muzaffarpur, Bihar 842001, India.
E-mail: jitendrakumarpaswan481@gmail.com

Sippy Kumari Research Scholar, University Department of Physics, B.R.A. Bihar University, Muzaffarpur, Bihar 842001, India.
E-mail: sippykumari04@gmail.com

***Corresponding author:** **Sippy Kumari** Research Scholar, University Department of Physics, B.R.A. Bihar University, Muzaffarpur, Bihar 842001, India.
E-mail: sippykumari04@gmail.com

Received on 11.04.2020
Accepted on 12.10.2020

ABSTRACT We have studied the electromagnetically induced transparency for a two level ensemble interacting with two orthogonal optical modes. We have made a approach for a multimode silicon waveguide coupled to a plasmonic resonator array. We have shown that a simple periodic ensemble of resonant metal nanoparticles within a dielectric waveguide supported a transparent waveguide plasmon polariton mode for guided slow light propagation. Such systems inhert the strongly dispersive properties of the nanoparticles embedded in the waveguide but do not succumb to the associated absorptive losses by utilizing the system's transparency Light propagation through the system provided extremely strong dispersion from the resonators, but suffers very low propagation loss by exploiting the system's transparency. Dispersion is controllable by tuning the coupling strength of localized plasmon and waveguide modes. We have found that atomic electromagnetically induced transparency occurred for a non zero pump field allowing mutual coupling of all states and induced destructive quantum interference of the probe field's absorption via the transition. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Electromagnetic induction, Transparency, Ensemble, Orthogonal, Multimode, Resonator Array, Waveguide, Plasmonic.

INTRODUCTION

Boller et al.[1] studied that quantum interference of electronic levels in an atomic ensemble, addressed by optical pump and probe fields, creates a highly dispersive response leading to a large group index of the probe field. A number of reports have suggested classical analogues of electromagnetically induced transparency arising from the selective coupling of multiple photonic elements with an optical field[2-7]. This is a static phenomenon due to wave interference, such systems exhibited the same highly dispersive responses as in atomic ensemble. Xu et al.[8] and Totsuka et al.[9] presented classical analogues of electromagnetically induced transparency in coupled plasmonic or photonic resonators.

Electromagnetically induced transparency is a phenomenon in quantum optics for its capability to slow down and even stop light[10] with potential applications in all optical memories[11] and enhanced optical nonlinearity[12]. Alam and Kumar[13] derived expressions that generalized the impedance concept for wave guiding devices from the microwave frequency regime to optics and plasmonics. Their expressions were based on electromagnetic eigen modes that are excited at the interface of a structure. They observed that impedance for the reciprocity based overlap of eigen modes. They found that applicability of simple circuit parameters ends and how the impedance can be interpreted beyond any particular point. Alam and Kumar[14] analysed the anomalous electromagnetic response of composite nanoparticle formed by two conjoined half cylinders of arbitrary complex permittivity and radius. They solved the complete scattering problem associated with this geometry derived closed from expressions for the induced fields inside and outside this composite particle. They found that this absorption paradox has been shown to be associated with singularities in the geometry and the adiabatic focusing of broad band surface plasmons supported at the corners. Kumar and Ranjan[15] studied transmission through surface disordered wave guides in general and solid basis. Their results showed that desired transmission properties on a waveguide through the roughness of its boundaries can be obtained. This surface scattering approach predicted that how mode specific scattering lengths waveguides depend on the details of system's surface roughness. They found that an observed shift of the amplitude scattering gap could be attributed to the nonvanishing disorder strength. They also found that short wave lengths can exhibit effects predicted for systems with long range correlations leading to drastic changes in their transmission properties. Kumar et al.[16] studied electromagnetic characteristics of carbon nanotube based antennas in different frequency regimes ranging from the microwave to visible. They observed that intershell tunneling qualitatively changed the form of effective boundary conditions in a double wall carbon nanotube in comparison to the electric field on the surfaces of different shells get coupled, which effect leaded to a generalized susceptibility that contained the mutual surface conductivities of both shells. Liu et al.[17] presented that mode group velocities and their coupling to the plasmonic resonators could be controlled through electro-optic modulation. Mori et al.[18] and Vlasov et al.[19] showed that the change in resonator position tunes the relative coupling strengths of TM_0 and TM_1 modes to the localized plasmon mode effectively impedance matching the light as it is slow down. Li etal[20] studied that to store 11 sub-ps pulses in a distance of $180\mu m$ and comparable to that of photonic crystal systems. Lukyankchuk et al.[21] studied that when all modes are degenerate, the zero frequency splitting normal is a linear combination of the two orthogonal modes, the third mode is not excited and essentially transparent within the coupled system. The obtained results were compared with the previous obtained results.

METHOD

We have made a approach for a multimode silicon waveguide coupled to a plasmonic resonator array. Each nanoparticle exhibits a localized plasmon resonance near the telecom frequency with dipole orientation along the z-axis. The nanoparticles extinction spectrum and $|E|^2$ distribution near resonance has been utilized. The calculations were performed using the finite element method and the empirical value. An incident fundamental transverse magnetic mode TM_0 is resonantly scattered by the localized plasmon mode that couples to either backward travelling TM_0 or TM_1 modes, depending on the resonator period. A waveguide plasmon polariton occurs when all three modes are degenerate at the different points. The coupling of localized plasmon and TM modes near a degeneracy point is described by a matrix equation based on the effective Hamiltonian

$$\left[\begin{pmatrix} \omega_0 - \upsilon_{gn}\Delta k & 0 & C_n \\ 0 & \omega_0 + \upsilon_{gm}\Delta k & C_m \\ C_n & C_m & \omega_0 + \delta + i\gamma \end{pmatrix} - \Omega\right]\begin{pmatrix} \psi_n \\ \psi_m \\ \psi_{lp} \end{pmatrix} = 0 \qquad \text{… (A)}$$

where ω_0 is the frequency at a point, the two modal propagation constants are related to the resonator period by $\beta_m(\omega_0) = \frac{2\pi}{\Lambda} - \beta_n(\omega_0) = k_{z0}$, $\Delta k - k_{z0}.\upsilon_{gi} = \frac{c}{n_{gi}}$., i = m or n are the local group velocities of the waveguide modes that approximate a linear mode dispersion near ω_0 and k_{z0}, c_i are mode coupling strengths to the localized plasmon mode, $\delta = \omega_{lp} - \omega_0$ is the detuning of localized plasmon mode and $[m,n]$ takes $[1,0]$ or $[0,0]$ for different points. The solution of equation (A) at k_{z0} gives three eigen frequencies:

$\Omega = \omega_0$ and $\Omega_{\pm} = \omega_0 + \frac{(\delta + i\gamma)}{2} \pm \sqrt{\frac{(\delta + i\gamma)^2}{4} + C_m^2 + C_n^2}$.

The eigenvector of the transparency mode $\psi_o = (C_m - C_n 0)(C_m^2 + C_n^2)^{-\frac{1}{2}}$ is a superposition of waveguide modes only i.e. the plasmonic resonance is cancelled out. The other two modes are the upper and lower edges of the coupling induced band gap of the system. Transparent waveguide plasmon polariton arise from the system's periodicity and are independent of the nanoparticles resonant properties. Only the group velocities control the peak of waveguide plasmon polariton group velocity at k_{z0},

$$\upsilon_g(\omega_0) = \frac{\partial \Omega(k_{z0})}{\partial k_z} = \frac{\upsilon_{gm} C_n^2 - \upsilon_{gn} C_m^2}{C_m^2 + C_n^2}.$$

RESULTS AND DISCUSSION

Figure (1) (a) shows dispersion relations for coupled localized plasmon and TM modes with various coupling strengths. Figure (1) (b) shows the central waveguide plasmon politron's retrieved group index. Figure (1) (c) and (d) also show the same information localized plasmon case with different detunings. For the coupling of different mode orders the slow light condition is attained by tuning the coupling strengths as shown in Figure (1) (a) and (1) (b). The highest possible group index requires different coupling strengths to compensate for the difference in the mode group velocities, such that

$$\frac{C_m}{C_n} = \sqrt{\frac{\upsilon_{gm}}{\upsilon_{gn}}}.$$

This is obtained by adjusting the resonator position in the waveguide core along the y-axis using the different field distributions of TM_0 and TM_1 modes as shown in Figure (1) (c). The group velocity for a waveguide plasmon polariton remains slow within a band width $\Delta\omega = \Omega - \omega_0$ with group index peaks at ω_0 has a full width half maximum band width of

$$\frac{\upsilon_g(\omega_0)}{k}\sqrt{\delta^2 + \gamma^2}.$$

Enhancement of the group index is achieved through the quadratic dependence on the coupling strength and by minimizing both the resonator losses and detuning. For slow light waveguide the localized plasmon and TM system is preferable for maximumally slowing down light. Efficient coupling to this band edge waveguide plasmon polariton from the outside may be achieved using slow wave injectors but the slow light band width is impractically narrow. The semiconductor platform is deal for exploiting nonlinearities toward achieving a dynamic system response, e.g. mode group velocities and their coupling to the plasmonic resonators could be controlled through electro-optic modulation. Such a system could be electrically addressed through the metal nanoparticle array.

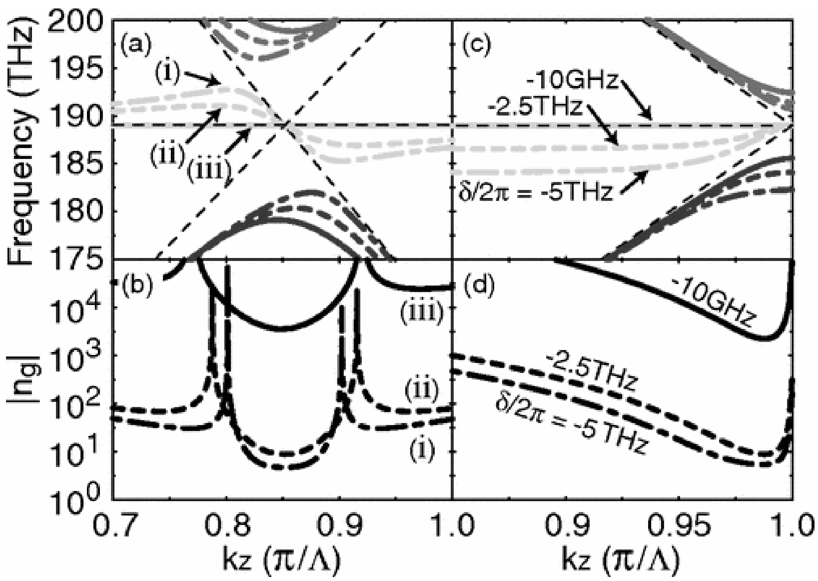

Figure 1: Dispersion relations of coupled localized plasmon versus TM_0 and TM_1 modes.

CONCLUSION

We have presented a physical mechanism for achieving a electromagnetically induced transparency for a two level ensemble interacting with two orthogonal optical modes. We have found that a simple periodic ensemble of resonant metal nanoparticles within a dielectric waveguide plasmon polariton mode for guided slow light propagation. Such systems inherit the strongly dispersive properties of the nanoparticles embedded in the waveguide. Dispersion is controllable by tuning the coupling strength of localized plasmon and waveguide modes, while maintaining extremely low loss at the system's transparency. Strong coupling in such plasmonic hybrid leaded to large group index band width products.

REFERENCES

1. Buller. K. J, Imamoglu. A and Haris. S. E, (1991), Phys. Rev. Lett., 66, 2593.
2. Zhang. S, Genov. D. A, Wang. Y, Liu. M and Zhang. X, (2008), Phys. Rev. Lett. 101, 047401.
3. Zentraf. T, Zhang. S, Oulton. R. F and Zhnag. X, (2009), Phys. Rev. B, 80, 195415.
4. Papasimakis. N, Fedotov. V. , Zheludev. N. I and Prosvirnin, (2008), Phys. Rev. Lett., 101, 253903.
5. Tassin. P, Zhang. L, Koschny. T, Economou. E. N and Soukoulis. C. M, (2009), Phys. Rev. Lett., 102, 053901.
6. Liu. N, Laugguth. L, Weiss. T, Kastel. J, Fleischhauer. M, Pfau. T and Geissen. H, (2009), Nat. Mater. 8, 758.
7. Kekatpure. R. D, Barnard. E. S, Cai. W and Brongersma. M. L, (2010), Phys. Rev. Lett. 104, 243902.
8. Xu. Q, Sandhu. S, Povinelli. M. L, Shakya. J, Fan. S and Lipson. M, (2006), Phys. Rev. Lett. 96, 123901.
9. Totsuka. K, Kobayashi. N and Tomita. M, (2007), Phys. Rev. Lett. 98, 213904.
10. Haris. S. E, (1997), Phys. Today, 50, 36.
11. Phillips. D. F, Fleischhauer. A, Mair. A, Walsworth. R. L and Lukin.M. D, (2001), Phys. Rev. Lett. 86, 783.
12. Harris. S. E, Field. J. E and Imamoglu. A, (1990), Phys. Rev. Lett. 64, 1107.
13. Alam Abdul Sttar and Kumar Ashok, (2019), J. BPAS, 38D, Phys., No-1, p-46.
14. Alam Abdul Sttar and Kumar Ashok, (2019), J. BPAS, 38D, Phys., No-1, p-27.

15. Kumar Upendra and Ranjan Ravi, (2019), J, BPAS, 38D, Phys., No -2, p-60.
16. Kumar Niranjan, Das Anil Kumar Lal and Kumar Ashok, (2018), J, BPAS, 37, Phys., No -1, p-19.
17. Liu. A, Jones. I, Liao. L, etal, (2004), Nature (London), 427, 615.
18. Mori. D and Baba. T, (2004), Appl. Phys. Lett. 85, 1101.
19. Valasov. Y. A and Mcnab. S. J, (2006), Opt. Lett. 31, 50.
20. Li. J, White. T. P, Faolain. L. O, Gomez-Iglesias. A and Krauss. T. F, (2008), Opt. Express, 16, 6227.
21. Luk Yanchuk. B, Zheludev. N. I, Maiser. S. A, Halas. N. J, Nordlander. P, Geissen. H and Chong. C. T, (2010), Nat. Mater. 9, 707.