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Coupled Plasmonic Metallic Nanowires to Induce Localization of Surface Plasmon Polaritons

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ABSTRACT We have studied the influence of the structural disorder on the spatial distribution of the plasmonic field and its propagation in one and two dimensional arrays of coupled metallic nanowires. By solving the three dimensional Maxwell equations we have studied the Anderson localization of surface Plasmon polaritions for arrays of metallic nanowires with varying degree of the structural disorder. We have found that a random distribution of radii of the nanowires leaded to transverse spatial localization of collective surface plasmonic polarition excitations. The characteristic spatial confinement of the plasmonic field found smaller than the optical wavelength which demonstrated that plasmonic structures can be employed to implement the subwave length Anderson localization of the electromagnetic field. We have also found that influence of the metallic loss and the gain of the host medium on the plasmonic Anderson localization modes, loss was compensated by the gain whose strength was much smaller than the loss rate of the metallic component of the plasmonic array. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Structural Disorder, Spatial Distribution, Plasmonic Arrays, Coupled, Metallic Nanowires, Polaritions, Localization.

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INTRODUCTION

Vasic et al. [1], Bauer et al. [2] and Iorsh et al. [3] studied that the use of periodic arrays of nanowires made it possible to engineer the effective optical dispersion with an unprecedented degree of flexibility. The structural disorder was inevitably introduced by nano fabrication, or purposely built into the system, affected the physical properties of the plasmonic crystals and thus limited the functionality of sub wavelength plasmonic nanodevices. The structural disorder profoundly affects the spectrum of wave modes, with the Anderson localization being perhaps the most spectacular effect of that kind. This is a fundamental wave phenomenon, which was first predicted in solid state physics as the localization of electron wave functions in ordered lattices [4]. Later on Anderson localization was found as a ubiquitous effect that occurred in a multitude of settings in which waves interact with disordered potentials including light [5-7], matter waves [8-9] and sound [10]. The Anderson localization of surface Plasmon polaritions was predicted in metal-dielectric percolation composites [11] and the effects of randomly located scatters on surface Plasmon polaritions guiding along the surface of gold films were observed experimentally [12]. Raether [13], Zayats et al. [14] and Ozbay [15] presented an effective way to overcome a certain limitation to employ surface Plasmon polariton waves, whose strong confinement at the metallic surface and deep subwave length characteristic scale made it possible to achieve a strong coupling between the optical fields and nanosized photonic structures. A very promising approach toward the goal is to employ arrays of metallic nanowires also known as plasmonic crystals [15-18], where the optical coupling of surface Plasmon polaritons in adjacent nanowires is controlled by dielectric properties of the embedding medium [19-21]. A detailed deviation of the coupled mode theory leaded to the discrete schrodinger equation with a long range coupling was studied by Mihalache et al.[22] and coupled mode equation [23]. Chen et al. [24], Fei et al. [25] and Christensen et al. [26] studied terahertz spectral regions by using other plasmonic systems such as arrays of graphene ribbons. Miles et al. [27] applied a approach based on the full Maxwell equation system to the subwavelength localization of atomic excitations, a phenomenon that has been observed experimentally. Gupta and Mishra [28] presented an EQ approach to access the scaling potential of single nanowire transistors vs planar MOSFETS based on both gate control and quantum confinement. The results showed that the non planar nanowire structure, e.g. the cylindrical wire FET provided better gate control while displaying stronger quantum confinement than planar devices. Kumar and Ranjan [29] studied the transmission through surface disordered waveguides and effect of nanowire on coherent scattering. They found that the observed shifts and broadenings of the gaps are not experimental artifacts but a detail of Omitted facts was done by surface scattering theory. The later was derived for perturbatively small disorder amplitude. A theoretical study of antenna coupling predicted that coefficients depend weakly on frequency such that they can regard them a fitting constant.

METHOD

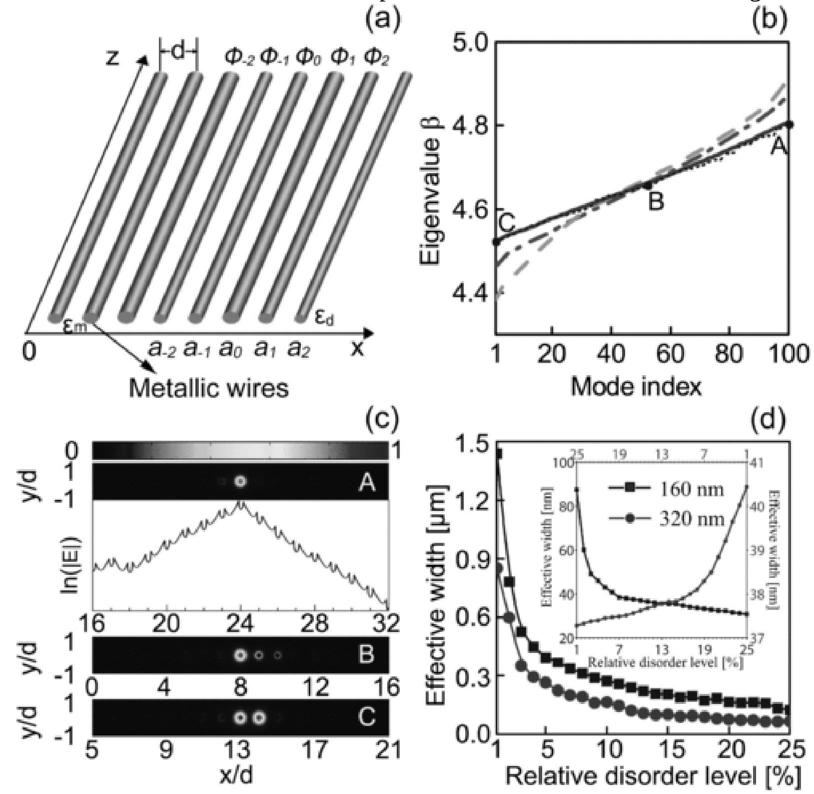
Considering one dimensional arrays of N coupled metallic nanowires oriented along the z-axis, being equally spaced in the transverse direction *x* by distance ‘d’. The structural disordered is introduced by fixing radii of the nanowires in the array, with discrete co-ordinate n, as $a_n = a + \delta_n$, where a is the average radius and δ_n is a random deviation. Assuming that δ_n is uniformly distributed in the interval of $[-\delta, \delta]$, with $\delta < a$, the level of the disorder being characterised by $\Delta \equiv \frac{\delta}{a}$. The equal spacing between nanowires makes different from fully random plasmonic structures, e.g. planar randomly distributed metallic scatterers with random sizes. Triangular fine mesh with a maximum size element of 10 nanometer was used. The resulting face mesh sweeps along the propagation direction of the nanowires with a step of 500 nanometer. Appropriate scattering boundary conditions were used to mimic open boundaries. A convergence analysis was conducted to ensure that the results. We have used the permittivity of dielectric material was $\in_m = 12.25$ which corresponded, e.g. to Si or GaAs and we have used the Drude model to describe the permittivity of the metal, $\in_m = 1 - \omega_p^2 / \left[\omega\left(\omega + iv\right)\right]$. The nanowires were made of silver with Plasmon damping frequencies $\omega_p = 13.7 \times 10^{14}$ rad s^{-1}. The Schrodinger equation with a long range coupling were used is

$$i\frac{d\phi_n}{dz} + b_n\phi_n + \sum_{j \geq 1} K_j \left(\phi_{n-j} + \phi_{n+j}\right) = 0$$

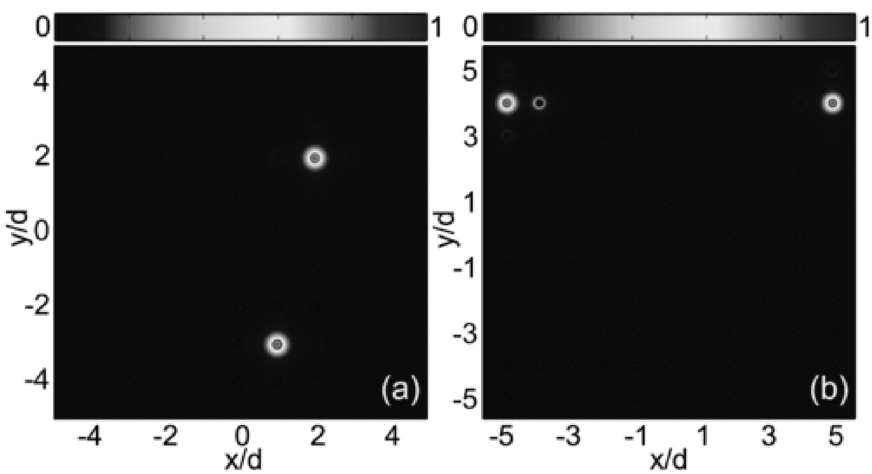
where b_n is the propagation constant of the mode associated with the *n*th nanowire.

RESULT AND DISCUSSION

Graph (1) (c) shows that when the disorder strength exceeds randomness strength nearly 5%, two strongly localized modes emerge at edge of the transmission band. Anderson localization modes near the bottom of the band were found unstaggered where as the Anderson localization modes at the top of the band were found staggered. Anderson localization modes located in the central part of the band feature is a fixed structure. When randomness strength increased then additional super modes became more localized and involved into Anderson localized modes. For all values of randomness strength at which the Anderson localization occurred the Anderson localization modes at the edges of the band are localized much stronger than near its centre. The ohmic loss in metallic nanowires causes decay of propagating Anderson localization modes which can make their observation. A promising scheme to offset the loss is to embed the array into a dielectric medium carrying optical gain, e.g. by pumped quantum dots or wells. Graph (2) shows two dimensional Anderson localization modes. The localization of surface polasmon polaritions is also possible in two dimensional disordered nanowire arrays. Which are similar to one dimensional case? We have found that there is deep subwave length confinement of the plasmonic field in both transverse directions is clearly observed. In one case the Anderson localization mode is formed inside the array it is known as bulk mode where as the other on e is located at the boundary of the array is known as surface Anderson localization mode. It was found that for a relatively weak disorder, the field is almost entirely confined around a single nanowire. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.



Graph 1: (a) A disordered plasmonic array. (b) The spectrum of supermodes of the array, averaged over an ensemble of 100 randomness realizations.



Graph 2: Anderson localization modes formed in a 2D disordered plasmonic array. (a) and (b) Intensity of the electric field in bulk and surface Anderson localization modes.

CONCLUSION

We have studied the localization of surface plasmon polaritions induced by metallic nanowires. The coupled mode theory equations provide more accurate description of plasmonic supermodes when only the nearest neighbor coupling is considered. A large discrepancy between the predictions of the coupled mode theory and three dimensional Maxwell equations were observed for the modes at the edges of the transmission band. The use of three dimensional Maxwell equations for modeling strongly coupled, high index-contrast systems such as plasmonic arrays yielded a coarse approximation for our purpose. By solving three dimensional Maxwell equations we hve demonstrated that the Anderson localization of surface plasmon polaritions can be achieved in one and two dimensional arrays of metallic nanowires with a varying degree of structural disorder. We have found that random variations of the radius of coupled plasmonic nanowires are sufficient to induce the Anderson localization of surface plasmon polaritions. We have studied the feasibility of the compensation of optical losses by means of embedded gain elements. We have found that the deep subwave length Andserson localized surface plasmonic polaritions may be maintained at extremely low gain or even without gain. The obtained results were found in good agreement with previously obtained results of theoretical and experimental works.

REFERENCES

[1]. Vasic. B and Gajic. R. (2012), Opt. Soc. Am. B, 29, 2964.
[2]. Bauer. C, Kobiela. G and Geissen. H, (2012), Sci. Rep. 2. 681.
[3]. Iorsh. I. V, Belov. P. A, Zharov. A. A, Shardrivov. I. V and Kivshar. Y. S, (2012), Phys. Rev. A, 86, 023819.
[4]. Anderson. P. W, (1958), Phys. Rev., 109, 1492.
[5]. John. S, (1984), Phys. Rev. Lett. 53, 2169.
[6]. Schwartz. T, Bartal. G, Fishman. S and Segev. M, (2007), Nature (London), 446, 52.
[7]. Lahini. Y, Avidan. A, Pozzi. F, Sorel. M, Morandotti. R, Christodoulides. D. N and Silberberg. Y (2008), Phys. Rev. Lett. 100, 013906.
[8]. Billy. J, Josse. V, Zuo. Z, Bernard. A, Hambrecht. B, Lugan. P, Clement. D, Sanchez- Palencia. L, Bouyer. P and Aspect. A, (2008), Nature (London), 453, 891.
[9]. Roati. G, Errico. C, Fallani. L, Fattori. M, Fort. C, Zaccanti. M, Modugno. G, Modugno. M and Inguscio. M, (2008), Nature (London), 453, 895.
[10]. Hu. H, Strybulevych. A, Page. J. H, Skipetrov. S. E and Va. Tiggelen. B. A, (2008), Nat. Phys. 4, 945.
[11]. Sarychev. A. K, Shubin. V. A and Shalaev. V. M, (1999), Phys. Rev. B, 60, 16389.
[12]. Bozhevolnyi. S. I, Volkov. V. S and Leosson. K, (2002), Phys. Rev. Lett. 89, 186801.
[13]. Raether. H (1988), Surface plasmons on smooth and rough surfaces and on gratings, Springer, Tracts in Modern Physics, Vol – III, (Springer, Berlin, 1988).
[14]. Zayats. A. V, Smolyaninov. I. I and Maradudin. A. A, (2005), Phys. Rep. 408, 131.
[15]. Ozbay. E, (2006), Science, 311, 189.
[16]. Bozhevolnyi. S. I, Erland. J, Losson. K, Skovgaard. P. M. W and Hvam. J. M, (2001), Phys. Rev. Lett. 86, 3008.
[17]. Kelf. T. A, Sugawara. Y, Baumberg. J. J. Abdelsalam. M and Bartlett. P. N, (2005), Phys. Rev Lett. 95, 116802.
[18]. Tao. A. R, Ceperley. D. P, Sinsermsuksakul. P, Neureuther. A. R and Yang. P, (2008), Nano. Lett. 8, 4033.
[19]. Ye. F, Mihalache. D, Hu. B and Panoiu. N. C, (2010), Phys. Rev. Lett. 104, 106802.
[20]. Ye. F, Mihalache. D, Hu. B and Panoiu. N. C, (2011), Opt. Lett. 36, 1179.
[21]. Kou. Y, Ye. F and Chen. X (2013), Opt. Lett. 38, 1271.
[22]. Ye. F, Mihalache. D and Panoiu. N. C (2013), in spontaneous symmetry Breaking, Self Trapping and Josephson oscillations, edited by B. A. Malomed, Progress in Optical Science and Photonics, Vol – I (Springer, Berlin, 20130) pp- 357-375.
[23]. Supplemental materials at http://link.aps.org/supplemental/10.1103/ PhysRevB.89.195428 for detailed derivation of the coupled mode equations.
[24]. Chen J etal (2012), Nature (London), 487, 77.
[25]. Fei. Z etal (2012), Nature (London), 487, 82.
[26]. Christensen. J, Manjavacas. A, Thongrattanasiri. S, Koppens. F. H. L and de Abajo. F. J. G, (2012), ACS Nano. 6, 431.
[27]. Miles. J. A, Simmons. Z. J and Yavuz. D. D., (2013), Phys. Rev. X, 3, 031014.
[28]. Gupta. B. K and Mishra Manish, (2018), Bulletin of Pure and Applied Sciences- Physics, Vol – 37, D, No-1, p - 1-6.
[29]. Kumar Upendra and Ranjan Ravi, (2019), Bulletin of Pure and Applied Sciences- Physics, Vol – 38, D, No-2, p – 60-64.

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