Optics Communications 329 (2014) 15–22

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dispersion-sensitive surface plasmon wave assisted by incoherent gain

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ARTICLE INFO

Article history:
Received 12 December 2013
Received in revised form
21 April 2014
Accepted 2 May 2014
Available online 14 May 2014

Keywords:
Surface plasmon wave
Dispersion sensitivity
Incoherent gain
Electric-dipole allowed transition

ABSTRACT

A three-level system with pumped electric-dipole allowed transition for incoherent-gain negative permittivity is suggested in order to realize dispersion-sensitive surface plasmon wave. The present surface wave modes occurring at an interface between an incoherent-gain negative-permittivity “plasmonic” medium (e.g., a semiconductor-quantum-dot material) and an ordinary dielectric can be amplified due to population transfer in the three-level system of the negative-permittivity medium. The issues of complex phase constant and the attenuation coefficients in the adjacent media are considered for addressing the problem of loss compensation of surface plasmon wave. The effect of incoherent-gain amplification exhibited by the dispersion-sensitive surface plasmon wave can be utilized for designing new quantum optical and photonic devices, e.g., photonic transistors and logic gates.

1. Introduction

Photonics at electromagnetic interfaces has a number of fascinating subjects [1]. One of them is *surface plasmonic photonics*, in which surface plasmon wave (and hence surface plasmon resonance and plasmon polariton) are the relevant concepts attracting intensive interest of many researchers [2]. Surface plasmon wave (SPW) is a kind of electromagnetic excitation (eigenmodes of the Maxwell equations), which propagates in the direction parallel to an interface between a dielectric and a conductor of negative permittivity, but decays evanescently (inside both media) in the perpendicular direction to the interface [1]. The surface plasmon resonance (SPR), which can be viewed as a process of excitation of surface plasmon modes, has been a fundamental physical mechanism for designing some devices, e.g., optical sensors, modulators [3,4] and biomolecular sensors [5]. Since surface plasmon modes can interact strongly with nanoscopic objects, it has led to various fields ranging from fundamental principles to application-oriented technologies, including many intriguing applications for designing new micro- and nanoscale photonic devices [1,2]. Recently, surface plasmon excitation (including SPR polaritons) has received extensive attention in optics, photonics, electronics and relevant technologies [6–12].

In order to offer working mechanisms for designing new photonic and quantum optical devices that have certain specific functions in practical applications, we shall here suggest a scheme for realizing *dispersion-sensitive* surface plasmon wave (see Fig. 1 for its schematic diagram). In general, the conventional SPWs were generated at an interface between a dielectric and a metal [1,2]. It should be pointed out that the relative permittivity, $\epsilon_{\rm r}^{(\rm Metal)}=1-\omega_{\rm p}^2/\omega^2$, of a metal is not sensitive to the frequency, since the variable (angular frequency ω) appears as $1/\omega^2$ in the permittivity. Obviously, the impact would be enormous if a dispersion-sensitive electrically resonant medium can be fabricated by using new scenarios such as quantum optical approach, where photonic resonance and quantum coherence are involved. Since multilevel systems, including atomic systems (e.g., in neutral alkali-metal atoms) and semiconductor-quantum-dot systems [13–17], are governed by quantum mechanics, in which the Schrodinger equation is a first-order differential equation of time t, the frequency in the permittivity, $\epsilon_{\rm r}^{(\rm SQD)}$, of a multilevel medium, e.g., a semiconductor-quantum-dot (SQD) material, will appear as $1/\Delta$ with $\Delta=\omega_{32}-\omega$, where ω_{32} denotes the level transition frequency and ω the mode frequency of the incident light (see Fig. 1(b)). The dispersion (close to the resonance frequency) in the permittivity of the multilevel medium is extremely large, e.g., 10^5 times that in a metal, namely,

$$\frac{\left|\dfrac{{\rm d}\epsilon_{\rm r}^{(\rm SQD)}}{{\rm d}\omega}\right|}{\left|\dfrac{{\rm d}\epsilon_{\rm r}^{(\rm Metal)}}{{\rm d}\omega}\right|}\simeq\frac{\omega}{|\omega_{32}-\omega|}\simeq 10^5, \qquad (1)$$

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http://dx.doi.org/10.1016/j.optcom.2014.05.005
0030-4018/

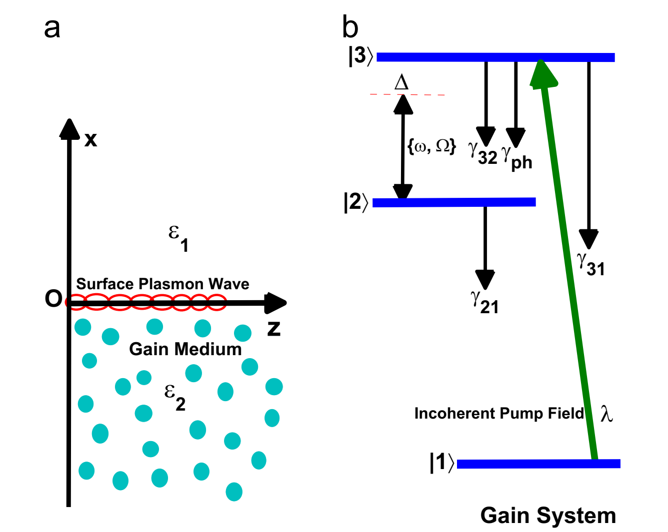

Fig. 1. The schematic diagrams of the geometry of a single, flat interface for sustaining surface plasmon wave (a) and an incoherent-gain-assisted three-level SQD (semiconductor-quantum-dot) system with a pumped electric-dipole allowed transition for realizing an incoherent-gain negative permittivity (b). The population at the ground level $|1\rangle$ is transferred by a pump field to level $|3\rangle$ (at a pumping rate λ). The level pair $|2\rangle$–$|3\rangle$ can be coupled to the electric field of an incident electromagnetic wave of mode frequency ω and Rabi frequency Ω.

where ω has the order of magnitude of 10^{15}–$10^{16}\ \mathrm{s}^{-1}$, and $|\omega_{32}-\omega|$ has the order of magnitude of 10^{10}–$10^{11}\ \mathrm{s}^{-1}$. As is known, such a dispersion-ultrasensitive behavior of multilevel medium is also the physical origin of slow light [18]. We expect that some new highly sensitive devices (e.g., SPW-based optical and biomolecular sensors [3–5]) would be realized if the present dispersion-sensitive optical response can be employed as a working mechanism. Besides, some photonic devices (e.g., photonic transistors and logic gates) could also be designed since an incoherent gain process [19–21] will be introduced in the present scheme. Such an incoherent gain process can lead to high gain optical amplification of the surface wave. In the literature, gain-assisted propagation loss compensation of surface plasmon modes by using various gain material structures, including multiple quantum wells [22,23], optically pumped dye polymer [24], Rhodamine dye molecules in solution [25], gain-medium-coated gold nanorod [26], metal-gain composition [27], and lead-sulphide quantum dots [28], has been studied either theoretically or experimentally. The relevant properties of low-loss and lossless surface plasmon wave, such as optical nonlinearity and plasmon-polariton transport, have been addressed [29–32]. In this paper, we shall consider the gain-assisted surface wave with emphasis on its dispersion sensitivity.

In this paper, we shall propose an experimentally feasible scheme for the dispersion-sensitive surface plasmon wave assisted by incoherent gain. Such an action of incoherent pumping would play two key roles in the present scheme: (i) it can make the multilevel SQD medium have a negative permittivity in order to support the existence of the surface plasmon wave modes at the interface (see Fig. 1(a)); (ii) it can give rise to high gain optical amplification of the surface plasmon wave. We shall consider the dispersion characteristics of the attenuation coefficients and phase constants of the incoherent-gain-assisted surface plasmon wave (the attenuation coefficients and phase constants are the most essential quantities for characterizing a surface electromagnetic wave mode). The spatial profile of the field strength of the surface plasmon wave will also be presented in the numerical example.

2. An incoherent-gain multilevel system

Consider a three-level system $\{|1\rangle, |2\rangle, |3\rangle\}$ (see the schematic diagram depicted in Fig. 1(b)). We assume that the two upper levels $|2\rangle, |3\rangle$ have the opposite parity and can give rise to electric-dipole allowed transition between them, and the parity of the ground level $|1\rangle$ is even. Such a three-level system can be found in some semiconductor quantum dots [13,14]. As an "*artificial*" atom, there is energy level structure in a quantum dot, and it can exhibit a number of effects of optical responses that atoms have [33]. Hence a thin semiconductor-quantum-dot material [34] (deposited upon the prism base), which can exhibit the effect of multilevel transitions, can serve as such an incoherent medium.

For the electric-dipole allowed transition, since level $|2\rangle$ and level $|3\rangle$ have the opposite parity, there is an electric-dipole transition moment $\wp_{32}$ in the transition process from level $|2\rangle$ to level $|3\rangle$, and the level pair $|2\rangle$–$|3\rangle$ can be coupled to the electric field of an incident electromagnetic wave of mode frequency ω and Rabi frequency Ω (see Fig. 1(b)). A pumping action that can lead to *incoherent population transfer* [19–21] will be introduced in order to pump the population at the ground level $|1\rangle$ to the upper level $|3\rangle$. This will make the "plasmonic" SQD gain medium have an electric permittivity with a negative imaginary part (characterizing the incoherent-gain amplification of the electromagnetic wave that drives the $|2\rangle$–$|3\rangle$ electric-dipole allowed transition).

According to the quantum mechanical Schrodinger equation, the equation of motion of the density matrix of the three-level system in Fig. 1(b) is given by

$$\begin{aligned}
\dot{\rho}_{11} &= -\lambda\rho_{11}+\gamma_{31}\rho_{33}+\gamma_{21}\rho_{22},\\
\dot{\rho}_{22} &= -\gamma_{21}\rho_{22}+\gamma_{32}\rho_{33}-\frac{\mathrm{i}}{2}\Omega\rho_{23}+\frac{\mathrm{i}}{2}\Omega^{*}\rho_{32},\\
\dot{\rho}_{33} &= \lambda\rho_{11}-(\gamma_{31}+\gamma_{32})\rho_{33}+\frac{\mathrm{i}}{2}\Omega\rho_{23}-\frac{\mathrm{i}}{2}\Omega^{*}\rho_{32},\\
\dot{\rho}_{32} &= -\left(\frac{\gamma_{31}+\gamma_{32}+\gamma_{21}+\gamma_{ph}}{2}+\mathrm{i}\Delta\right)\rho_{32}+\frac{\mathrm{i}}{2}\Omega(\rho_{22}-\rho_{33}),\\
\dot{\rho}_{23} &= -\left(\frac{\gamma_{31}+\gamma_{32}+\gamma_{21}+\gamma_{ph}}{2}-\mathrm{i}\Delta\right)\rho_{23}-\frac{\mathrm{i}}{2}\Omega^{*}(\rho_{22}-\rho_{33}),
\end{aligned}\tag{2}$$

where the diagonal density matrix elements ρ_{11}, ρ_{22}, and ρ_{33} agree with the constraint $\rho_{11}+\rho_{22}+\rho_{33}=1$. The Rabi frequency $\Omega=\wp_{32}\mathcal{E}_p/\hbar$ with $\wp_{32}$, $\mathcal{E}_p$ and $\hbar$ the transition electric-dipole moment, the field envelopes (slowly varying amplitudes), and the Planck constant, respectively. The parameters γ_{ij} ($i, j=1, 2, 3$) and γ_{ph} denote the spontaneous emission decay rates and the collisional dephasing rate, respectively. The parameter λ represents the pumping rate of the population from the ground level $|1\rangle$ to the upper level $|3\rangle$.

The electric field of the incident propagating wave can drive the electric-dipole allowed $|2\rangle$–$|3\rangle$ transition. Here, the steady density matrix elements ρ_{32} can be used to characterize this electric-dipole allowed transition. The expression for the electric polarizability of a single quantum dot (due to $|2\rangle$–$|3\rangle$ transition) is given by $\beta_e=2\wp_{23}\rho_{32}/(\varepsilon_0\mathcal{E}_p)$, which can also be rewritten as

$$\beta_e=\frac{2|\wp_{32}|^2}{\varepsilon_0\hbar\Omega}\rho_{32}.\tag{3}$$

Here, ε_0 denotes the vacuum permittivity. In order to achieve a negative permittivity, the dipole–dipole interaction between neighboring quantum dots must be strong, i.e., we should take into consideration the local field effect. The Clausius–Mossotti relation, which involves local field effect and can reveal the connection between the macroscopic permittivity (ε_r) and the microscopic polarizability (β_e), is of the form [35,36]

$$\varepsilon_r=\frac{1+\frac{2}{3}N\beta_e}{1-\frac{1}{3}N\beta_e},\tag{4}$$