The giant enhancement of Fano-type resonance in a gain-assisted silicon slab array*

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Giant resonance enhancement is demonstrated to be due to the Fano interference in a grating waveguide composed of gain-assisted silicon slabs. The Fano mode is characterized by its ultra-narrow asymmetric spectrum, different from that of a pure electric or magnetic dipole. The simulation indicates that a sharp Fano-interfered lineshape is responsible for the giant resonance enhancement featuring the small-gain requirements.

Keywords: giant resonance, photonic materials, gain, amplification

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1. Introduction

Resonance, along with an external pumping source and the stimulated emission of radiation, is a fundamental part of laser generation. To achieve a miniature version of a laser at the nanoscale, many kinds of resonant prototypes have been proposed to explore the performance of amplification efficiency, such as the defect mode in photonic crystal,[1] Fabry–Perot resonance in semiconductor nanowires,[2] whispering gallery mode in a nanopatch cavity,[3] and hybrid plasmon mode in a gap-waveguiding structure.[4] Moreover, surface plasmon amplification by stimulated emission of radiation (shortened as spaser),[5–7] as an interesting amplification phenomenon of plasmon resonance, is promising for plasmonic nanolasers, especially owing to the fact that some experimental progress has been made toward the lasing spaser.[8] For the mechanism of a spaser, the surface plasmon in a planar metallic structure oscillates in an eigenmode with a high quality factor (Q), and its stimulated emission is fuelled by the lossless energy transfer/coupling from an externally pumped gain medium adjacent to the plasmonic structure. Subsequently, it was clarified that a spaser can lase if an amplified trapped-mode resonance allows a fraction of the accumulated plasmon energy to radiate out.[6] The predominant aspect for a lasing spaser lies in the fact that a relatively small gain coefficient is sufficient to amplify the incident light, with the aid of stimulated emission of tightly confined surface plasmons. This advantage was attributed primarily to the induced coherent plasmon oscillation, the trapped mode (high Q), as well as the photon-like plasmon property.[6,8] Unfortunately, the experimental demonstration of a lasing spaser, up to date, has not shown intensity as strong as theoretically expected.[8] The discrepancy should be attributed not only to the overwhelming Ohmic loss in metal in the optical spectrum, but also to the possible experimental difficulties in realizing the hybridized energy transfer between two combined heterostructural systems (i.e., photons in a gain medium and plasmons in a metallic structure). In this sense, the surface plasmon resonance, on the other side of the coin, also poses an obstacle to the small-gain lasing effect. Consequently, it is wondered whether or not plasmon-free amplification phenomenon can be realized with a similar small-gain characteristic of the spaser if no metals are used .

As a matter of fact, the so-called trapped mode for a lasing spaser belongs to the Fano resonance, which is characterized by an asymmetric scattering line shape as well as a relatively narrow frequency response as compared with a symmetric Lorentz resonance.[6–9] Physically, the Fano resonance is a result of destructive and constructive interferences of quantum mechanism through coherent coupling between a broad background quasi-continuum state and a narrow discrete state.[10–13] Specifically, the transmission peak is a consequence of the constructive interference, while the accompanied transmission dip is caused by the destructive interference. Note that the Fano resonance is inherently with features of coherence and high Q, and it is in fact a universal phenomenon existing in various physical systems.[10–13] In this work, we investigate the giant enhancement effect by virtue of the Fano-type spectrum of a hybrid resonance in a silicon slab array to avoid the heavy optical loss in metal. In doing so, it is confirmed that the Fano mechanism with an intrinsic feature of coherent interference is the underlying reason for giant resonance enhancement with a small gain requirement.

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2. Fano-type resonance

For particles with arbitrary shapes, the Mie scattering theory is applicable to dealing with various resonant modes induced by incident electromagnetic waves.[14] Usually, only the electric and magnetic dipoles in spherical,[15] cubic,[16,17] cylindrical, and other shaped geometries are considered due to the predominant resonance intensities of these two fundamental modes.[18] Here we consider a structure composed of a planar silicon strip array ($n_{si} = 3.45$) with individual strip length $l = 650$ nm in the x direction, width $w = 150$ nm in the y direction, thickness $t = 150$ nm in the z direction, and periodicity $\Lambda = 750$ nm for both x and y directions, deposited on a quartz substrate $n_{quartz} = 1.55$. According to simulations based on the full-wave finite-element method,[19,20] the lowest-order resonance due to the Bragg diffraction of the grating is characterized by a standard Lorentz dip at 1.25 μm in the transmission spectrum when the incident wave with x polarization propagates along the z direction (the curve of $w = 150$ nm in Fig. 1(a)). Interestingly, this resonance can be gradually modified into a Fano-type transmission profile around 1.52 μm (the curve of $w = 650$ nm in Fig. 1(a)) by increasing the strip width w, with other scales kept unchanged. Moreover, the resulting Fano-type resonance in silicon slabs ("strips" with small ratio l/w due to the increased w) exhibits a certain capability of magnetic-field confinements [see Figs. 1(b) and 1(c) for this resonant mode], which should be a side-effect of the electric resonance of the slab. Obviously, this lowest-order mode has nothing to do with the extensively studied magnetic dipole resonance since it is excited by the incident E-field polarization. On the other hand, due to the resonant coupling between adjacent silicon particles, this mode is clearly not a pure electric dipole, but a hybrid resonant mode resulting from the interaction between the electric dipole resonance of the slab and the collective waveguiding mode of the array of slabs. As a matter of fact, a conventional eigenmode of a particle, such as an electric (or magnetic) dipolar resonance,[21] usually exhibits a resonant Lorentz lineshape in the spectrum, therefore the Fano-type asymmetric spectrum manifests itself as a hybrid resonant mode of two channels. To distinguish it from other lowest-order modes (i.e., the pure electric and magnetic dipoles), it will be demonstrated that this Fano-type resonant mode is attributed to the interference effect of the light through the grating-modulated waveguiding structure, which contributes greatly to the low-threshold lasing.

As mentioned earlier, a Fano-type response physically indicates that there is an interference effect between two channels with different decay times. For the considered configuration, one channel is the direct transmission portion through the silicon structure, and the other is attributed to the diffraction portion of the silicon grating which induces the waveguiding mode within the laterally-aligned slab layer.[22,23] For slabs with $l = w = 650$ nm and thickness $t = 150$ nm in the normal incident case, the silicon array itself also acts as a waveguiding layer with the effective index of refraction $n_{eff}^2 = F \times n_{si}^2 + (1-F) \times n_{gap}^2$, where $F = V_{si}/(V_{si} + V_{gap})$ is the filling factor of silicon slabs in the effective waveguiding layer. For such an asymmetric waveguide configuration with a quartz substrate and an air superstrate, the mode condition for the TE mode to propagate within the waveguiding layer can be written as[24]

$$\tanh t = \frac{p+q}{h(1-pq/h^2)},$$

with

$$h = \sqrt{n_{eff}^2 k_0^2 - \beta^2}, \quad q = \sqrt{\beta^2 - n_{air}^2 k_0^2}, \quad p = \sqrt{\beta^2 - n_{quartz}^2 k_0^2}.$$

For an incident light at 1.54-μm vacuum wavelength ($k_0 = 4.08\ \mu m^{-1}$), this silicon slab layer can support a waveguiding mode with the calculated propagation constant $\beta = 9.38\ \mu m^{-1}$, approximately matching the reciprocal grating vector $G = 2\pi/\Lambda = 8.38\ \mu m^{-1}$. The difference between β and G is mainly due to the effective refractive index (n_{eff}) approximation of the dielectric layer.[25,26] The Fano-type spectrum is a result of the phase interference between the grating waveguide channel and the direct transmission channel.[22,23] In this sense, the considered mode can be regarded as a hybrid resonance of grating-modulated waveguiding mode, in contrast to a first-order multipole mode such as an electric or magnetic dipole. In addition, it should be emphasized that a strong dielectric resonance due to the Mie scattering can be expected only in a microwave regime with high-permittivity materials such as ferroelectric ones.[16] The optical Mie resonance in a semiconductor is unavoidably weaker than surface plasmon resonance, especially in the sense of the capability of the electromagnetic field confinement. However, the semiconductor Mie resonance can result in small loss, and an optical waveguide layer can be formed in this configuration, in contrast to the metallic structure. In fact, the Fano-type resonance is obviously shown in the spectrum, as a result of the matched low-loss waveguiding mode in the slab-array layer interfering with the Mie scattering of the individual particles of the silicon slab.

The above analytical model is in good accordance with the numerical Fano-type spectrum shown in Fig. 1(a), as far as the resonant wavelength is concerned. However, for a small value of w, adjacent silicon slabs with given Λ are less coupled due to the large gap $g = \Lambda - w$ and thus it cannot be considered as an effective waveguiding layer with n_{eff}. As a result, the resonant spectrum loses its Fano-type asymmetric characteristic but behaves as a dipole-like Lorentz spectrum [Fig. 1(a), $w = 150$ nm]. In fact, according to the simulation results, for a given silicon grating periodicity Λ and thickness t, smaller gap (better waveguiding layer approximation

for a homogeneous n_{eff}) will lead to a narrower Fano-type line shape (Fig. 2), indicating a stronger Fano interference caused in the grating waveguide structure. Nevertheless, an almost complete transmission peak and a zero-transmittance dip at a nearby wavelength remain there regardless of the linewidth of the Fano-type spectrum, as a result of the constructive and the destructive interference, respectively. It will be shown that the lossless Fano-type transmission maximum, as well as its narrowband response (high Q), is the key factor contributing to the small-gain amplification in the metal-free resonant silicon slabs.

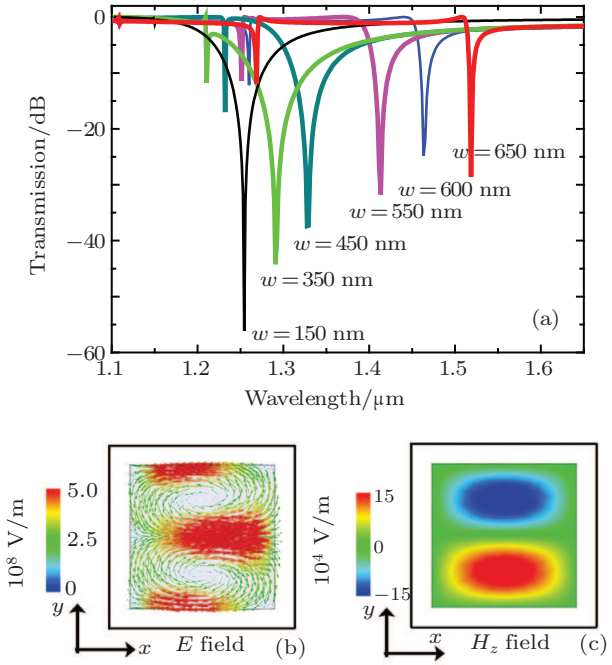


Fig. 1. (color online) (a) The transmission spectra of a planar silicon slab array with different slab widths. (b) and (c) The electric and magnetic field distributions for the Fano-type resonance at $w = 650$ nm, where the dashed back lines mark the silicon slabs.

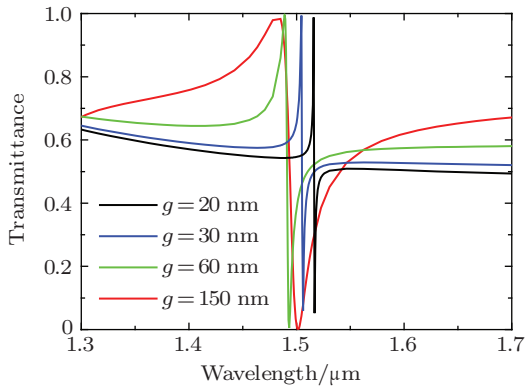


Fig. 2. (color online) Fano interference modulation by tuning the gap between silicon slabs. A stronger Fano-interference spectrum (narrower line shape) indicates better phase matching between the propagation constant of the waveguiding mode and the grating reciprocal vector.

3. Resonance enhancement characteristic

To investigate the Fano-type resonance enhancement in the grating waveguide structure, an active layer is introduced as shown in Fig. 3. The considered Fano-type resonant structure is a planar array of squared silicon slabs (refractive index $n_{\text{si}} = 3.45$) with an underlying thin active layer of polymethylmethacrylate (PMMA, $n_{\text{PMMA}} = 1.49$) doped with active materials such as PbS quantum dots. The substrate is a quartz glass ($n_{\text{quartz}} = 1.55$). Each of the squared silicon slabs is 650-nm edge long, 150-nm thick, and the gap g between neighboring slabs is tunable to modulate the line shape of the Fano-type resonance. The gain coefficient α is used for the active characteristic of the photopumped PbS semiconductor, described by a Gaussian function with a maximum value at 1.5-μm wavelength and an assumed full width at half maximum (FWHM) 150 nm. Mathematically, the gain coefficient is written as $\alpha = (2\pi/\lambda)\,\text{Im}(\sqrt{\varepsilon' + \text{i}\varepsilon''})$, where ε' is the real part and ε'' is the imaginary part of the electric permittivity.[6,19]

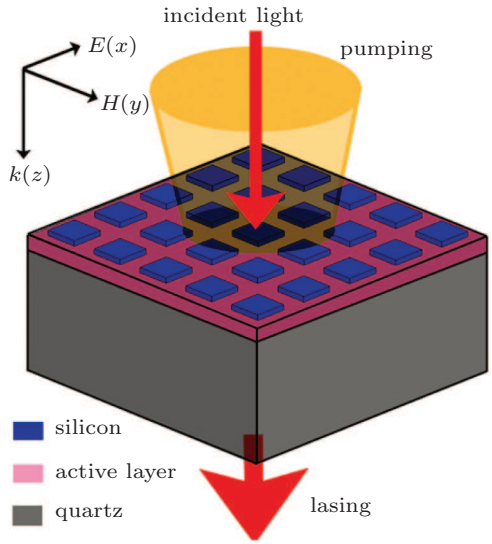


Fig. 3. (color online) Structural configuration for the Fano-type grating waveguide laser.

From Figs. 4(a) and 4(b), it is found that for the semiconductor-based slab array a pronounced amplification effect can be obtained from the Fano-type resonant mode. Interestingly, a small gain coefficient $\alpha = 450$ cm^{-1} is enough for the amplification effect as long as a small gap $g = 30$ nm holds, while a gain value α as large as 5000 cm^{-1} will be necessary for the amplification effect if g is increased to 150 nm. This result is consistent with the theoretical analysis provided earlier, which implies physically that a constructive interference, corresponding to the lossless Fano peak in the transmission spectrum, can significantly contribute to the amplification effect, since the ultra-narrow Fano-type resonant spectrum induces a very high Q value. Note that the small gain requirement demonstrated in our simulations is based on an idealistic slab structure so that the quality factor of the narrow Fano resonance only reflects the confinement loss. In reality, other losses, such as surface roughness and defects, would outweigh confinement loss for such an ideal high-Q mode.

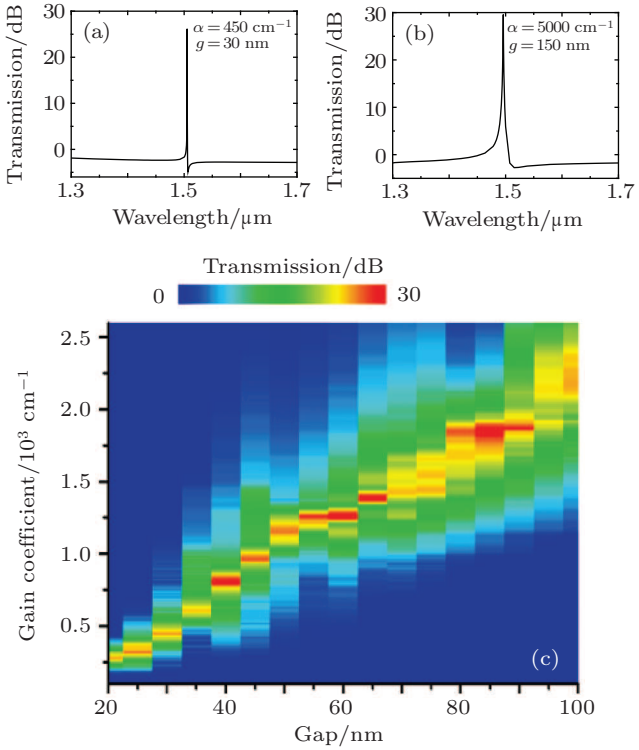


Fig. 4. (color online) (a) Low-gain enhancement for a small gap $g = 30$ nm. (b) High-gain enhancement for a large gap $g = 150$ nm. (c) The gain dependence of the enhancement effect at the modulation of gap between slabs. Note that a smaller gap means a stronger Fano interference as shown in Fig. 2.

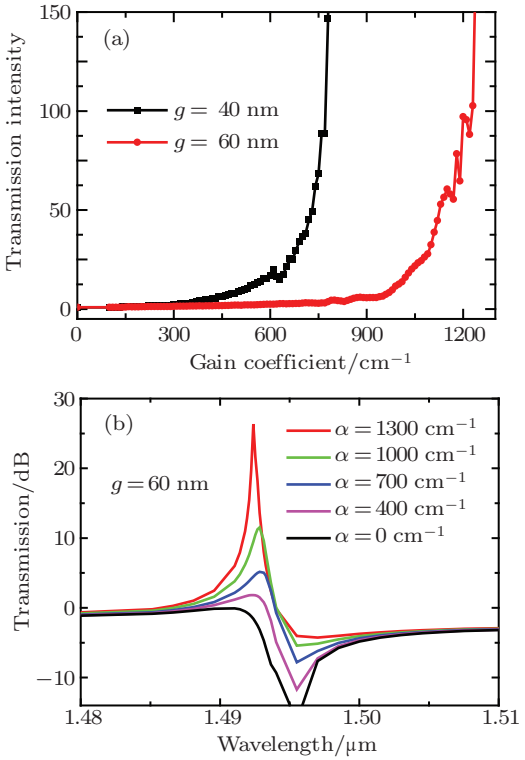


Fig. 5. (color online) (a) Curves of enhanced transmission intensity versus gain coefficient. (b) The transmission amplifications of the Fano spectrum under different gain values.

In addition, the simulation results shown in Fig. 4(c) clearly indicate that a large gain coefficient will be required for a weak Fano interference (i.e., for large gap cases) to be amplified. Therefore, a broadband Lorentz-type resonance like a pure electric-dipole resonance, instead of a narrow Fano-type resonance, will need a huge gain coefficient to obtain the giant amplification phenomenon. This viewpoint can also be found in a recent theoretical work.[27] On the other hand, the gain coefficient to trigger the amplification from the Fano-type silicon slab array is also considerably lower than that expected in a metal-based lasing spaser, which may be attributed to the fact that no Ohmic loss is expected for the semiconductor.

To evaluate the gain coefficient required for the Fano-resonance amplification, the amplified transmission intensity dependences on gain coefficient are shown in Fig. 5(a). It is found that the threshold gain coefficients are about $\alpha_{\text{th}} = 650\ \text{cm}^{-1}$ and $1000\ \text{cm}^{-1}$ for gap $g = 40$ nm and 60 nm, respectively. The amplification spectra at different gain coefficients, or the FWHM, can be estimated according to Fig. 5(b).

4. Summary and conclusion

In this work, we demonstrate that a Fano-type grating waveguide mode in a silicon slab array, with the assistance of a gain medium layer, can significantly contribute to the amplification of the incident light at a low gain threshold. We conclude that a pronounced Fano-type spectrum is an important characteristic to realize the small-gain-required amplification by a structured array, which can avoid the loss issue of a metal-based structure since the Fano response is universal in various material systems. Moreover, the proposed semiconductor-based structure with low threshold for giant enhancement can work in the visible spectrum since some semiconductors in this wavelength regime, such as cadmium sulfide (CdS), have high refractive indices for the grating waveguide as well as high gain coefficients.

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