

Efficient third-harmonic generation based on Tamm plasmon polaritons

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Received January 7, 2013; revised February 15, 2013; accepted February 15, 2013;
posted February 19, 2013 (Doc. ID 182877); published March 14, 2013

We theoretically investigate efficient third-harmonic generation (THG) in the heterostructure with a one-dimensional photonic crystal (PC) and a thick metal film. There are both the fundamental Tamm plasmon mode and the high-order mode in the heterostructure. Commonly these two Tamm plasmon modes just satisfy single-resonance condition, but the double-resonance condition can be fulfilled by using a binary PC in the heterostructure. Taking advantage of the tunneling effect of Tamm plasmon modes, THG in the single-resonance heterostructure is enhanced over 3 orders of magnitude more than that in the single metal film, and that in the double-resonance one is further enhanced nearly 2 orders of magnitude. © 2013 Optical Society of America

OCIS codes: 190.2620, 160.3918, 160.5298, 240.0240.

Recently Tamm plasmon polaritons (TPPs) have attracted researchers' interest. As a type of interface mode that can be excited directly, TPPs can strongly localize the electric fields at the interface between a one-dimensional photonic crystal (1DPC) and a thick metal film [1–4]. By utilizing very large nonlinear permittivities or magneto-optical constants of metals, TPPs can enhance the salient optical effects of metals, including the nonlinear response, extinction, and Faraday rotation effects (see [5,6] and references therein). The enhanced optical effects of metal could be used for the designs of optical switches and diodes, absorbers and insulators.

In this Letter, we study efficient third-harmonic generation (THG) based on TPPs. It is known that resonant structures can be used to improve nonlinear optical generation [7]. In general, surface plasmon modes play important roles in the enhancement of second harmonic generation in metallic nanoparticles [8] and THG in metallic nanostructures, such as 1D gratings [9,10], two-dimensional apertures [11], and three-dimensional magnetic metamaterials [12]. By comparison, TPPs provide an efficient and simple method for THG due to their properties of direct optical excitation. In particular, third-harmonic radiation could be greatly enhanced when TPPs are excited simultaneously both at the fundamental frequency of light and at its third harmonic frequency, which is called double-resonance enhanced THG. Compared to a single metal film, THG only in the single-resonance heterostructure can be enhanced over 3 orders of magnitude, which is comparable with surface-plasmon-enhanced THG [13], and that in the double-resonance one can be even enhanced over 5 orders of magnitude.

We first investigate the usual 1DPC-metal heterostructure. Here the planar multilayer structure proposed is composed of a 1DPC and a thick metal film on a substrate, which is denoted by $(AB)_NMS$. The dielectric A is NaF with refractive indices $n_A(1064 \text{ nm}) = 1.321$, $n_A(355 \text{ nm}) = 1.336$ [14] and thickness $d_A = 194 \text{ nm}$, respectively. The dielectric B is MgO with refractive indices

$n_B(1064 \text{ nm}) = 1.722$, $n_B(355 \text{ nm}) = 1.776$ [14], and thickness $d_B = 149 \text{ nm}$, respectively. The number of period N is chosen as 11. The substrate S is K9 glass with refractive index $n_S = 1.52$. The metal M is silver with thickness $d_M = 100 \text{ nm}$. The permittivity of silver is described by the Lorentz–Drude model [15]

$$\varepsilon(\omega) = \varepsilon_{r,\infty} + \sum_{k=0}^K \frac{f_k \omega_p^2}{\omega_k^2 - \omega^2 + j\omega\Gamma_k}, \quad (1)$$

where $\varepsilon_{r,\infty}$ is the dielectric constant at infinite frequencies, ω_p the plasma frequency, and ω_k , f_k , and Γ_k are the resonance frequency, strength, and damping frequency, respectively, of k th oscillator. The Lorentz–Drude model uses K damped harmonic oscillators to describe the small resonance observed in the metal's frequency response. The values of the constants in Eq. (1) are taken from [15]. At 1064 and 355 nm, we obtain the permittivity of silver $\varepsilon_M(1064 \text{ nm}) = -47.1 + 3.25i$ and $\varepsilon_M(355 \text{ nm}) = -1.44 + 0.62i$, respectively.

Supposing light was normally incident on the structure in the z direction, we use the transfer-matrix method [16] to calculate the reflectance spectra (R). It can be seen from Fig. 1(a) that a reflectance dip appears at wavelength 1064 nm, which locates in the forbidden gap of the PC $(AB)_NS$. The reflectance dip with near-zero reflection ($R = 0.01$) indicates TPP mode. The PC in the gap has the effect of mu-negative materials and resonant tunneling occurs when it is combined with an epsilon-negative metal [5]. In physical essence, when the sum of the reflection phase at the left interface of 1DPC and at the right interface of the metal film is the integer times of 2π [1], a TPP resonance mode will appear. The Q factor of TPP mode could reach $\sim 10^4$ if the absorption in metal was supposed as zero. In fact, the Q factor of TPP mode decreases to ~ 200 due to metal's intrinsic loss. Owing to the tunneling effect, TPPs enhance fields greatly within thick metal film, as is shown in Fig. 1(b). Besides, we also

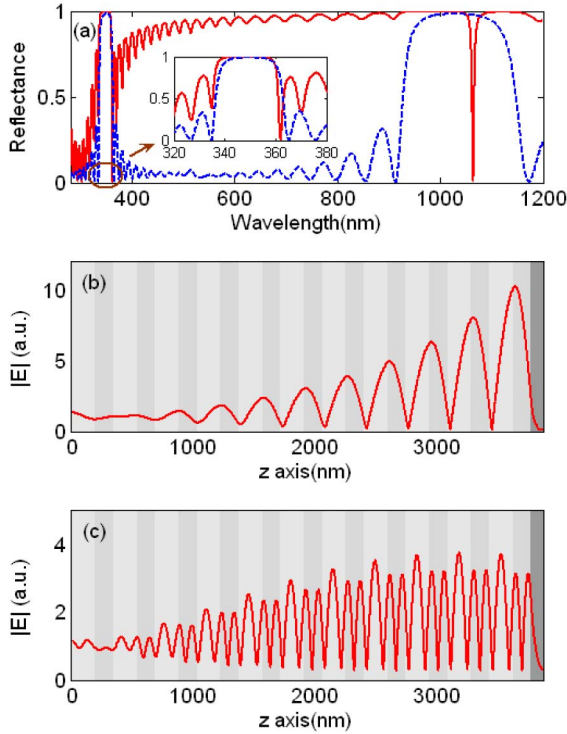


Fig. 1. (Color online) (a) Reflectance spectra of the heterostructure $(AB)_NMS$ (the red line) and the PC $(AB)_NS$ (the blue line) with $d_A = 194$ nm, $d_B = 149$ nm, $d_M = 100$ nm, and $N = 11$. The inset indicates the detail of high-order TPP mode. (b) Electric field distribution of fundamental TPP mode. The deep gray layer represents the silver film. (c) Electric field distribution of high-order TPP mode.

notice that another reflectance dip appears in the second gap of the PC $(AB)_NS$ at wavelength 362 nm with the reflectance $R = 10^{-3}$. This reflectance dip thus indicates high-order TPP mode and that in the first gap of the PC is called the fundamental mode. The resonance condition is also satisfied at the high-order TPP mode. Differently, the high-order mode locates at the edge of the second gap due to the rather small permittivity of silver at wavelength 355 nm. For the tunneling effect, the small permittivity of metal film requires small effective parameters of the gap of the PC, which corresponds to the gap edge [5]. The Q factor of high-order TPP mode reaches ~ 150 . The high-order TPP mode also enhances fields considerably within metal film that is described in Fig. 1(c). However, the frequency of the high-order TPPs is not three times of the frequency of the fundamental mode. Therefore, the heterostructure just is a single-resonance one for THG.

To further improve the conversion efficiency of THG, we design a double-resonance structure. Recent studies [17] have shown that the structure with binary periodicity, such as binary metamaterials, can provide extra degree of freedom to tune the reflection phase of the photonic band gap, and then can be used for double-resonance enhanced harmonic generation. Therefore we suggest that the heterostructure is composed of a metal film and a 1D binary PC, which is denoted by $(ABA'B')_NMS$. Based on the parameters of A layer and B layer in the single-resonance structure, we tune the thicknesses of $A(A')$ layer and $B(B')$ layer a little bit to make both fundamental and third harmonic frequencies satisfy the resonance

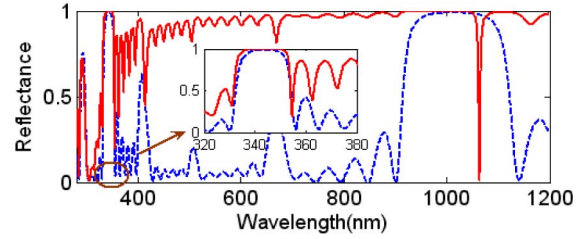


Fig. 2. (Color online) Reflectance spectra of the double-resonance heterostructure $(ABA'B')_NMS$ (the red line) and the PC $(ABA'B')_NS$ (the blue line) with $d_A = 174$ nm, $d_B = 132$ nm, $d'_A = 207$ nm, $d'_B = 160$ nm, and $N = 6$. The inset indicates the detail of high-order TPP mode.

conditions. The parameters of dielectrics are selected to be $d_A = 174$ nm, $d_B = 132$ nm, $d'_A = 207$ nm, $d'_B = 160$ nm, and $N = 6$, while the parameter of metal is unchanged. Under these parameters, resonance TPP modes occur both at 1064 and 355 nm. This means that the structure is a double-resonance one for THG. Its reflectance spectra are illustrated in Fig. 2.

Now we investigate the enhanced THG in the heterostructure. The THG process is treated in the nondepleted pump approximation because the THG process is weak enough that their effect on the incident wave is negligible. Therefore the THG process is described by nonlinear wave equation as follows:

$$\frac{d^2}{dz^2} E_{3\omega} + \frac{(3\omega)^2 \varepsilon_{3\omega}(z)}{c^2} E_{3\omega} = -\frac{(3\omega)^2}{c^2} \chi^{(3)}(z) E_{\omega}^3, \quad (2)$$

where ε_{ω} , $\varepsilon_{3\omega}$ are the linear permittivity of the fundamental wave (1064 nm) or third-harmonic wave (355 nm), respectively. $\chi^{(3)}(z)$ is the third-order susceptibility of silver at 1064 nm, which is supposed to be 1.9×10^{-11} esu [18]. The THG process can be obtained by solving Eq. (2) with the nonlinear retrieval method based on transfer matrix [19].

For the single-resonance enhancement of THG based on TPPs, the parameters of structure are chosen as those in Fig. 1. The input intensity of fundamental wave is taken to be 500 MW/cm². It can be seen from Fig. 3(a) that conversion efficiency η of THG in the single-resonance structure exhibits a peak value 5.5×10^{-10} when the wavelength of fundamental wave is 1064 nm, which is consistent with Fig. 1. For comparison, we also consider THG in a thick silver film. Under the same conditions, i.e., normal incidence and input intensity 500 MW/cm², the conversion efficiency of THG in the thick silver film with thickness 100 nm is only 1.7×10^{-13} . In other words, THG in the single-resonance heterostructure is enhanced over 3 orders of magnitude compared with that in a single silver film.

In particular, THG in the double-resonance heterostructure can be further enhanced. The parameters of structure are chosen as those in Fig. 2. Under the same conditions, the conversion efficiency of THG in the double-resonance heterostructure reaches a peak value of 5×10^{-8} when the wavelength of FF wave is 1064 nm. Such enhancement is over 5 orders of magnitude more than that in a single silver film and even is

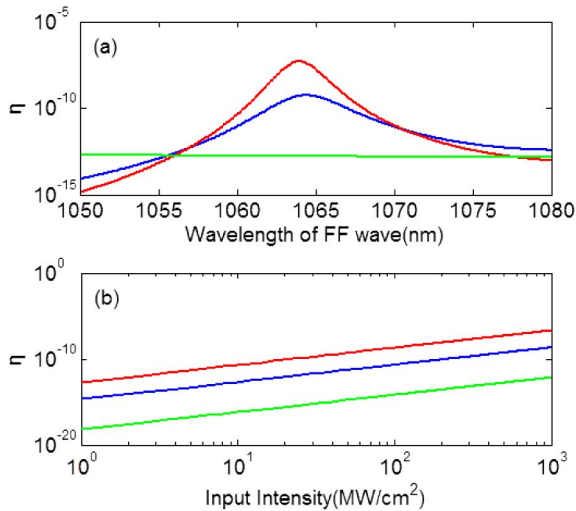


Fig. 3. (Color online) (a) Frequency dependence of conversion efficiency η of THG in the structure. (b) Dependence of the conversion efficiency via the input intensities at the wavelength 1064 nm. The red, blue, and green lines represent the double-resonance heterostructure (in Fig. 2), the single-resonance heterostructure (in Fig. 1), and the silver film with thickness of 100 nm, respectively.

nearly 2 orders of magnitude more than that in the single-resonance heterostructure.

In Fig. 3(b), we plot the input power versus the conversion efficiency of THG at 1064 nm. The conversion efficiency of THG in the single silver film is just 6.6×10^{-13} even if the input intensity of fundamental wave reaches 1 GW/cm^2 . However, under the same conditions, the conversion efficiencies of THG in the single- and double-resonance structures reach 2.1×10^{-9} and 2×10^{-7} , respectively, with the corresponding intensities of THG 2.1 W/cm^2 and 200 W/cm^2 .

In summary, we investigated efficient THG by utilizing TPPs. There are both the fundamental TPP mode and the high-order mode in the 1DPC-metal heterostructure. Commonly, the heterostructure is a single-resonance structure for THG. However, double-resonance heterostructure can be obtained by properly choosing binary PC. Under tunneling effect of TPPs, THG in the single- and double-resonance structures are enhanced over 3 or nearly 5 orders of magnitude, respectively, compared with that in the single metal film. It is shown that surface-plasmon-assisted THG can be enhanced over 3 orders of magnitude more than that in the single metal film [13]. Therefore, the single-resonance enhancement of Tamm-plasmon-assisted THG is comparable with surface-plasmon-assisted THG, and the double-resonance enhancement of

Tamm-plasmon-assisted THG is much higher than the surface-plasmon-assisted THG. We expect that the efficient Tamm-plasmon-assisted THG can provide new opportunities for the development of nonlinear dark-field microscopy from biological imaging to failure analysis of materials and devices [20].

This work was supported by the National Basic Research Program of China (No. 2011CB922001), by the National Natural Science Foundation of China (No. 11074187, 11264003, 11004121 and 11234010) and by the Guangxi Natural Science Foundation (No. 2012GXNSFAA053012).

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