Giant Enhancement of Third- and Fifth-Harmonic Generations in Epsilon-Near-Zero Nanolayer

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Abstract: We numerically demonstrate the third- and fifth-harmonic generations in epsilon-near-zero indium tin oxide metasurface. The conversion efficiency of 2.64×10^{-4} and 1.55×10^{-6} have achieved for the third- and fifth- harmonic generations.

1. Introduction

More recently, epsilon-near-zero (ENZ) materials have drawn enormous interests in nonlinear optics and nanophononics [1, 2]. ENZ behavior have been observed at highly doped semiconductors, such as transparent conducting oxides (TCOs). Among TCOs, indium tin oxide (ITO) is the most studied ENZ media for integrated photonics. ITO has revealed its advantages of large optical nonlinearity, enhanced harmonic generation under ENZ conditions [1–3]. In this work, we numerically study the third- and fifth- harmonic generations by integrating an ITO nanolayer into a metasurface structure at telecommunication wavelength. We show that the giant enhancement of the harmonic generation is larger than the metasurface without ITO, and the enhancement is closely related to ENZ mode. Moreover, the conversion efficiency of the third- and fifth- harmonic generations are 2.64×10^{-4} and 1.55×10^{-6} under the laser power of 60 mW.

2. Results and Discussions

The design of the ENZ ITO integrated metasurface is shown in Fig. 1(a). The structure is composed of gold rings, an ENZ ITO nanolayer (T = 20 nm), and a glass substrate. The gold rings are arranged in a periodic square array with a periodicity of 650 nm, which can be characterized by three geometrical parameters: inner radius r_i = 115 nm, outer radius r_o = 145 nm, and thickness h = 50 nm. The complex relative permittivity of ITO can be described by the Drude model:

$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega}, \tag{1}$$

here, ε_∞ = 3.8055 is the permittivity at the infinite frequency, ω is the angular frequency of incident light, and Γ =1.39× 10^{14} rad/s is the Drude damping rate [3]. The real part of the permittivity is assumed to fall to zero at λ_{ENZ} = 1550 nm when plasma frequency ω_p = 2.38× 10^{15} rad/s. The third-order susceptibility ($\chi^{(3)}$) of Au and ENZ ITO are set to be 7.71×10^{-19} m^2/V^2 [4] and 3.5×10^{-18} m^2/V^2 [5], respectively.

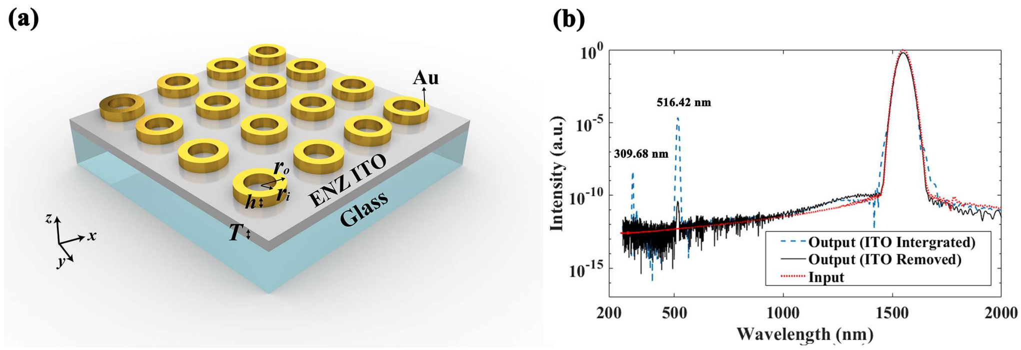

Fig. 1. (a) 3D schematic overview of the proposed structure. (b) The normalized spectrum of the input light source (red dotted line), the ENZ ITO integrated metasurface (blue dashed line), and the ENZ ITO-removed metasurface (black solid line).

To explore the harmonic generation of the proposed structure, a laser pump source of 100 fs at telecommunication wavelength of 1550 nm with an average power of 10 mW, a repetition rate of 80 MHz and a laser spot radius of 10 μm is used. The finite-difference time-domain (FDTD) method (Lumerical FDTD solutions) is used to numerically analyze the proposed device, and the data are collected from the reflection spectrum above the metasurface. The results show that the ENZ ITO integrated metasurface can produce obvious third- and fifth-harmonic generations at 516.42 nm and 309.68 nm, as shown by the blue dashed line in Fig. 1(b). The intensity of the third- and fifth- harmonic generations are ~6×10^6 and ~3.5×10^3 higher than that of the ITO removed metasurface (Au-glass substrate metasurface, black solid line). Upon defining the conversion efficiency as the ratio between the intensity of the output generated harmonic waves and the input light source, we calculated the ITO integrated metasurface conversion efficiency of the third- and fifth- harmonic generations are 2.16×10^{-5} and 4.74×10^{-9}, respectively. Figure 2(a) presents the $|E|^2$ distribution of the ENZ ITO integrated metasurface at an input wavelength of 1550 nm, where the polarization of light is along the horizontal axis of *x*. The $|E|^2$ distribution is mainly distributed and strongly enhanced in the ITO nanolayer, which is consistent with ENZ mode [6]. Such results indicate that the enhanced third- and fifth- harmonic generations of the ENZ ITO integrated metasurface is closely related to ENZ mode. Figure 2(b) shows the conversion efficiency of the third- and fifth- harmonic generations depending on the input laser power from 10 mW to 60 mW. The conversion efficiency of the third- and fifth-harmonic generations increases with the increase of the laser power, and reaches up to 2.64 $\times10^{-4}$ and 1.55×10^{-6} under 60 mW respectively.

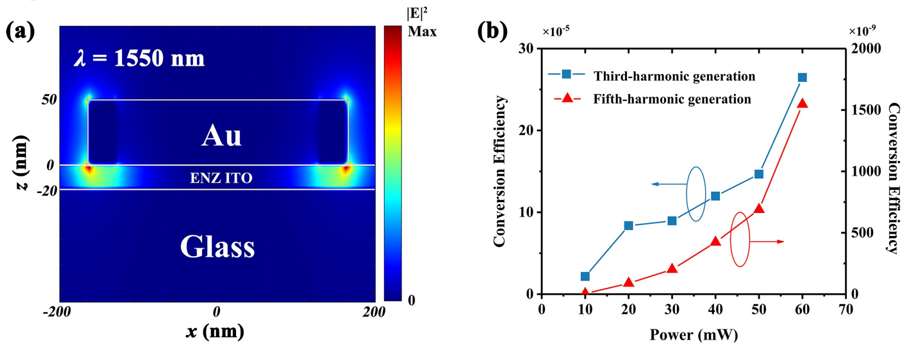

Fig. 2. (a) The field distribution $|E|^2$ at an input wavelength of 1550 nm of the proposed structure. (b) Relationship between the conversion efficiency of the third- and fifth- harmonic generations and the input laser power.

3. Conclusions

We numerically demonstrated the giant enhancement of third- and fifth-Harmonic generations in the ENZ ITO integrated metasurface at 1550 nm. By integrating the ENZ ITO into the metasurface, the intensity of third- and fifth- harmonic generations are ~6×10^6 and ~3.5×10^3 higher than that of the ITO-removed metasurface. The field distribution indicates the giant enhancement is closely related to ENZ mode. The high spectral conversion efficiency of 2.64×10^{-4} and 1.55×10^{-6} are achieved for the third- and fifth- harmonic generations under the input laser power of 60 mW, respectively.

Acknowledgments

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