Optical bistability in subwavelength metallic grating coated by nonlinear material

Changjun Min, Pei Wang, Xiaojin Jiao, Yan Deng and Hai Ming

Department of Physics, University of Science and Technology of China, Hefei, Anhui, 230026, P.R. China

Abstract: A developed two-dimensional Finite Difference Time Domain (FDTD) method has been performed to investigate the optical bistability in a subwavelength metallic grating coated by nonlinear material. Different bistability loops have been shown to depend on parameters of the structure. The influences of two key parameters, thickness of nonlinear material and slit width of metallic grating, have been studied in detail. The effect of optical bistability in the structure is explained by Surface Plasmons (SPs) mode and resonant waveguide theory.

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References and links

1. Introduction

Since Ebbesen first reported the extraordinary optical transmission through a two-dimensional metallic hole array in 1998 [1], there has been much interest in researches of Surface Plasmons (SPs) excited in subwavelength metallic structures, which opens up a new avenue for designing new types of metallic nano-optic devices [2-6]. In the coming years, a great challenge that faces SPs research is achieving active control of plasmonic signals in nano-optic devices [7]. So recently, nonlinear optical devices based on subwavelength metallic structures have been proposed to actively control plasmonic signals by nonlinear material [8-11]. Compared with usual all-optical devices based on various types of optical nonlinearities, these new nonlinear optical devices have advantages of mini-size and stronger nonlinear effects enhanced by electromagnetic field confinement and enhancement in metallic structures. However, properties of nonlinear optical effects (e.g., bistability) in these new devices should be studied further before taking into applications.

In this paper, a developed two-dimensional FDTD method has been used to investigate the optical bistability in a one-dimensional subwavelength metallic grating coated by a Kerr nonlinear material layer. Strong SPs can be excited in the structure and enhance the nonlinear effect. The whole structure is very simple and easily fabricated, which has great applications in designing actively controlled nano-optic devices, such as all-optical switching. The aim of this paper is to understand the properties of optical bistability in the structure and find how to get better bistability effect. The influences of two important parameters, thickness of nonlinear material and slit width of metallic grating, are discussed in detail. The simulated results of optical bistability are explained by SPs mode and resonant waveguide theory.

2. Simulation method and model

![Fig. 1. Schematic view of the nonlinear metallic structure under study: a metallic grating of period \( p \), metallic film thickness \( h \), slit width \( w \), and nonlinear material layer thickness \( d \). A TM-polarized plane wave is incident vertically from the top of the structure.](image)

In Fig. 1, we show a schematic view of the structure under study. Unless otherwise stated, the chosen parameters of the metallic grating are: \( p=1.44, w=0.3 \) and \( h=0.1 \) \( \mu \)m. A TM-polarized plane wave vertically illuminates the structure from the top with the wavelength at \( \lambda=1.55 \) \( \mu \)m, which is the typical wavelength used in telecommunications. The metallic grating is covered by a Kerr nonlinear material layer (thickness \( d \)), whose dielectric constant \( \varepsilon_d \) depends on the intensity of electric field \( |E|^2 \):

\[
\varepsilon_d = \varepsilon_l + \chi^{(3)} |E|^2, 
\]

where \( \varepsilon_l \) is the linear dielectric constant and \( \chi^{(3)} \) is the third-order nonlinear susceptibility. In what follows, the linear dielectric constant is chosen to be \( \varepsilon_l=2.25 \); the third-order nonlinear susceptibility is chosen as a typical value of nonlinear optical materials, such as InGaAsP, that is \( \chi^{(3)}=1\times10^{-18} \text{m}^2/\text{V}^2 (=1.4\times10^{-10} \text{esu}) \) [12].

A developed two-dimensional finite difference time domain (FDTD) method has been performed in our work. The second-order Lorentz dispersion model [13] is used to simulate
the metallic film. In order to account for the optical bistability, we import the nonlinear polarization vector $P_{nl} = \varepsilon_0 \chi(3)E_3$ [12] to the Maxwell equation of our FDTD program:

$$\nabla \times H = \varepsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t} + \frac{\partial P_{nl}}{\partial t}$$

(2)

where $\varepsilon_0$ is the relative dielectric constant at infinite frequency in the Lorentz model, $P_l$ is the linear polarization vector generated by the Lorentz model. Calculating with increasing or decreasing intensity of incident light, the nonlinear FDTD program results in two different transmission spectra, which compose a whole bistability loop. The periodic boundary conditions (PBC) [14] have been used in the boundaries parallel to the propagating direction of the light in the grating structure. The perfectly matched layer (PML) [15] has been used in the other boundaries. The used metal here is Ag with the dielectric constant $\varepsilon_m = -86.64 + i8.74$ at the wavelength of 1.55 $\mu$m, other dielectric constants are taken from values in [16]

3. Simulation results and discussion

First of all, we consider the optical bistability associated with the transmission peak caused by SPs excitation. Here we choose the thickness of nonlinear layer $d=0.88 \mu$m. Figure 2(a) shows the far-field transmission spectra corresponding to SPs excitation at different intensities of incident light. The intensities are chosen as $I=|E|^2=1 \times 10^{14}$, 2.25 $\times 10^{16}$ and 4 $\times 10^{16}$ $V^2/m^2$ respectively. In Fig. 2(a), it is obvious that the transmission peak red-shifts as the intensity increases, which can be explained by the SPs theory. The wavelength of transmission peak enhanced by SPs in metallic grating is approximately obtained from [18]:

$$\lambda_{sp} = \frac{p}{m} \text{Re} \left( \frac{E_x E_m}{\sqrt{E_x + E_m}} \sin \theta \right) (m=1, 2, 3 \ldots)$$

(3)

where $\varepsilon_m$ is the dielectric constant of metal, $\varepsilon_d$ is the dielectric constant of nonlinear material on metal surface, $\theta$ is the incident angle of the light hitting the metal surface. Although the light is incident vertically in our structure, $\theta$ is not ignorable for scattering light on metal surface. According to Eq. (1) and Eq. (3), when the incident intensity grows, $\varepsilon_d$ is augmented by nonlinear response and then makes the wavelength $\lambda_{sp}$ larger, hence the transmission peak red-shifts, as shown in Fig. 2(a).

In Fig. 2(b), a clear bistability loop is shown at the wavelength $\lambda=1.55 \mu$m. T1 and T2 denote the transmissions respective obtained from increasing and decreasing intensity of incident light.

In Fig. 2(b), a clear bistability loop is shown at the wavelength $\lambda=1.55 \mu$m. T1 and T2 in Fig. 2(b) denote the far-field transmissions obtained from the increasing and decreasing
intensity of incident light, respectively. When the intensity increases, the transmission $T_1$ jumps to a higher value in a discontinuous manner around $I=1.7\times10^{16} V^2/m^2$. By contrast, when the incident intensity decreases, the transmission $T_2$ keeps a high transmittance situation and follows the upper branch in Fig. 2(b).

In order to know the properties of bistability and get better results, we investigate some structure parameters and find two key parameters: nonlinear layer thickness $d$ and slit width $w$, which can be controlled to enhance the bistability effect. The influence of thickness $d$ is introduced firstly. Figure 3(a) shows the far-field transmission spectra versus thickness $d$ at different intensities of incident light. The incident wavelength is $\lambda=1.55 \mu m$ with intensities $I=1\times10^{14}, 2.25\times10^{16}$ and $4\times10^{16} V^2/m^2$. In Fig. 3(a), three sharp peaks can be observed at all intensities, which presents the periodic situation of far-field transmission. The value of transmission period is about $\Delta d\approx0.74 \mu m$ at low intensity ($I=1\times10^{14} V^2/m^2$), and it decreases when the intensity grows to high values.

The periodic effect of far-field transmission in Fig. 3(a) can be explained by metallic waveguide theory. The whole structure is considered as a metal/dielectric/air three-layer optical waveguide structure, and the waveguide mode equation is expressed as [17]:

$$ d \sqrt{k_0^2 \varepsilon_d - k^2} = m\pi + \phi_{12} + \phi_{23} \quad (m=0, 1, 2,...) \quad (4) $$

where $k_0=2\pi/\lambda$ is the wave vector of incident light, $k=2\pi/p$ is the wave vector of the metallic grating, $\phi_{12}$ and $\phi_{23}$ are the accompanied phase changes respective at the air/dielectric and dielectric/metal interfaces, both independent to the thickness $d$ of nonlinear layer. When Eq. (4) is satisfied by periodic values of thickness $d$, the resonant waveguide mode is formed in the nonlinear layer. Hence more incident energy is restricted in the nonlinear layer and
coupled with SPs, which strongly enhance the far-field transmission, as shown in Fig. 3(a). The transmission period $\Delta d$ can be concluded from Eq. (4) as follow:

$$\Delta d = \pi f \sqrt{k^2 \varepsilon_d - k} \tag{5}$$

If the incident intensity is low enough, the dielectric constant $\varepsilon_d \approx \varepsilon_i = 2.25$, then we can obtain the value of period $\Delta d=0.742\mu m$, coincident with the result $\Delta d=0.74\mu m$ in Fig. 3(a) at low intensity ($I=1.10^{14}V^2/m^2$). When the intensity grows to high values, $\varepsilon_d$ increases and the transmission period $\Delta d$ decreases according to Eq. (5), also shown in Fig. 3(a).

The bistability loop has been shown in Fig. 2(b) at $d=0.88\mu m$, which is close to the middle transmission peak in Fig. 3(a). Next, we consider the bistability effect associated with other two peaks in Fig. 3(a), shown in Figs. 3(b) and 3(c). The thicknesses of nonlinear layer are respectively chosen as $d=0.16$ and $1.62\mu m$, which result in different bistability effects. In Fig. 3(b), the bistability loop is hard to be observed, for the upper and lower branches almost overlap together. By contrast, the bistability loop at $d=1.62\mu m$ is rather obvious, which shows larger difference between upper and lower branches.

In order to compare the bistability effect influenced by thickness $d$ exactly, we show the transmission ratio $(T_2/T_1)$ in Fig. 3(d), which expresses the ratio of upper and lower branches of bistability loops. The more ratio $(T_2/T_1)$ is, the more obvious bistability loop can be observed. In Fig. 3(d), it is easy to find that higher peak of $(T_2/T_1)$ appears at larger thickness $d$. The highest peak of $(T_2/T_1)$ exceeds $100$ at $d=1.62\mu m$. The physical origin of the bistability and the influence of nonlinear layer thickness can be understood taking into account the optical resonant waveguide mode. It is well known that optical bistability often appears at some optical resonant structure containing nonlinear material, for example, the Fabry-Pérot resonant cavity. In our structure, the bistability originates from the resonant waveguide mode in the nonlinear layer. The waveguide mode can gather the EM-field energy of incident light to enhance nonlinear effect in the nonlinear layer and excite SPs on metal surface. The role of SPs is to enhance nonlinear effect around metal surface and transmit energy to slits. If the thickness $d$ becomes larger, more energy can be gathered in nonlinear layer and enhance the total nonlinear effect, hence the nonlinear dielectric constant and transmission both keep at a high situation with decreasing intensity, resulting in a more significant bistability loop.

Besides the thickness $d$ of nonlinear layer, the slit width of metallic grating also has great effect on optical bistability. We vary the slit width $w$ to study its influence at fixed thickness $d=0.88\mu m$ and wavelength $\lambda=1.55\mu m$. The bistability loops at $w=0.1, 0.2$ and $0.4$ $\mu m$ are shown in Figs. 4(a), 4(b) and 4(c) respectively. The bistability loop at $w=0.2\mu m$ is most significant, whose bistable region is wider than $w=0.1$ and $0.4$ $\mu m$. The relationship between slit width and bistability loop is further studied in Fig. 4(d), which shows the transmission ratio $(T_2/T_1)$ at different slit widths, from $w=0.1$ to $0.5$ $\mu m$. It is easy to find that the best result appears at $w=0.16\mu m$ with a peak more than $20$, and nearly no peak can be observed at the slit width more than $w=0.4\mu m$. Moreover, the position of peak shifts to high intensity when the slit width increases in Fig. 4(d), which means optical bistability can be carried out at a low intensity with suitable slit width.

The influence of slit width on optical bistability also can be explained taking into account the optical resonant waveguide mode. In our structure, the waveguide mode only exists at metal/dielectric/air structure, so larger slit width gives smaller waveguide region, which results in a weaker bistability effect. If the slit width is more than $w=0.4\mu m$, the resonant waveguide mode is destroyed, and more energy transits the slits directly instead of transmitted by SPs, hence the bistability loop is hard to be observed, as shown in Fig. 4(c). However, if the slit width is too small (e.g., $w=0.1\mu m$), the energy of incident light is hard to transit the slits, which also results in a weaker bistability effect, as shown in Fig. 4(a). So there should be an optimal slit width for optical bistability in the structure, which can supply both high transmission and enough waveguide region.

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Fig. 4. The transmission versus incident intensity at the chosen slit width: (a) $w=0.1\mu m$ (b) $w=0.2\mu m$ (c) $w=0.4\mu m$. The thickness of nonlinear layer is fixed at $d=0.88\mu m$ and the wavelength is $\lambda=1.55\mu m$. (d) The transmission ratio ($T_2/T_1$) of upper and lower branches of bistability loop is shown at different slit widths $w$ versus incident intensity.

Given available incident light and Kerr nonlinear material, this structure should be experimentally accessible and have great applications. For instance, some new polymers can present a third-order nonlinear susceptibility up to $10^{-6}\text{esu}$ and show ultrafast time response, which can be used in the structure for a high-sensitive ultrafast all-optical switching.

4. Conclusion

In this paper, we have investigated the optical bistability in a one-dimensional subwavelength metallic grating coated by a Kerr nonlinear material layer. Various bistability loops have been showed using a developed two-dimensional FDTD method. Two key parameters of structure, thickness of nonlinear layer and slit width, have been detail studied to find their influences and get better bistability loops. The physical mechanism about optical bistability in the structure has also been discussed by Surface Plasmons mode and metallic waveguide theory. This work will be helpful for designing new types of nonlinear metallic nano-optic devices, and contribute to more applications.

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