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Mode-matched Fano resonances for all-optical switching applications

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ABSTRACT

We introduce the concept of mode-matched Fano resonances in one-dimensional, subwavelength, diffraction gratings. These resonances are characterized by an extremely high quality (Q)-factor and lend themselves well for applications to ultra-low power, all-optical switching devices at telecommunication wavelengths. We provide examples of diffraction gratings made of a chalcogenide glass (As_2S_3) where, thanks to the mode-matched Fano resonances, all-optical switching is obtained at local field intensities well below the photo-darkening threshold of the material.

1. Introduction

Fano resonances [1] originate in any classical or quantum system that admits discrete modes coupled with continuum modes. For an up to date review of their importance in many fields of physics the reader can consult Refs.[2,3]. Due to the particular high quality (Q)-factor available in this kind of resonance, several studies have suggested their possible use for low-power, all-optical switching devices [4,5]. In a recent work [6] we have shown that a simple, one-dimensional (1-D), sub-wavelength, diffraction grating, made of a chalcogenide glass (As_2S_3) [7], with very narrow slit apertures (a ~ 12 nm) can lead to all-optical switching threshold of few tens of MW/cm^2 input intensities and local field intensities in the glass ~15 GW/cm^2. In this case the Q-factor of the Fano resonance was ~10^4. Slits so narrow can be fabricated [8], but are at the border of current nanofabrication techniques. Chalcogenide glasses are known to posses high values of the cubic nonlinearity and low two-photon absorption, which would make them optimal candidates for all-optical switching devices [7], were it not for the detrimental effect played by the photodarkening threshold (~1–10 GW/cm^2 local intensity) typical of chalcogenide materials [9]. Because the switching threshold scales as $1/Q^2$ [6] and the intensity in the glass scales as Q, the overall local intensity at the switching points will scale as 1/Q, therefore having resonances with high Q-factors is imperative in order to stay below the photodarkening threshold of the chalcogenide glass. In this paper we propose a method for further increasing the Q-factor of the Fano resonances available in subwavelength gratings mitigating at the same time the need of extremely narrow slits. We call these resonances as "mode-matched" Fano resonances for the reasons that will become clear in a moment. In Section 2 we present our analysis.

2. Results and discussions

Let us start our analysis with Fig. 1(a) where we show the geometry we analyze: a TE-polarized, monochromatic, plane wave is incident normally on a subwavelength, As_2S_3, diffraction grating grown on a glass substrate. The grating parameters are the following: period $\Lambda = 864$ *nm*, thickness $d = 200$ *nm*, n_f is the refractive index of the material filling the slits while a is the slit aperture. We consider three gratings with different slit apertures: respectively $a = 12$ *nm*, $a = 48$ *nm* and $a = 96$ *nm*. In our case Fano resonances are generated by leaky waveguide modes which are coupled to the incident radiation through the following grating-coupler-like equation [6]:

$$\sin(\vartheta) \cong \left| \pm n_{WG} \mp m\frac{\lambda}{\Lambda} \right| , \quad m = 0, 1, 2, \ldots, \tag{1}$$

where ϑ is the incident angle of the incoming radiation, λ the incident wavelength, n_{WG} the real part of the effective index of the mode of the unperturbed waveguide (in our case the air/As_2S_3(200 nm)/substrate waveguide), Λ the grating period and m the diffraction order. The grating dimensions have been chosen so to have a Fano resonance in the telecommunication band (~1.5–1.6 μm) according to Eq.(1). As previously discussed in Ref. [6], one way to increase the Q-factor of the Fano resonances would be by reducing the slit size a of the grating so that the grating gets closer and closer to the unperturbed waveguide resulting in an increased dwell time of the leaky waveguide mode generated inside the grating. Obviously there are

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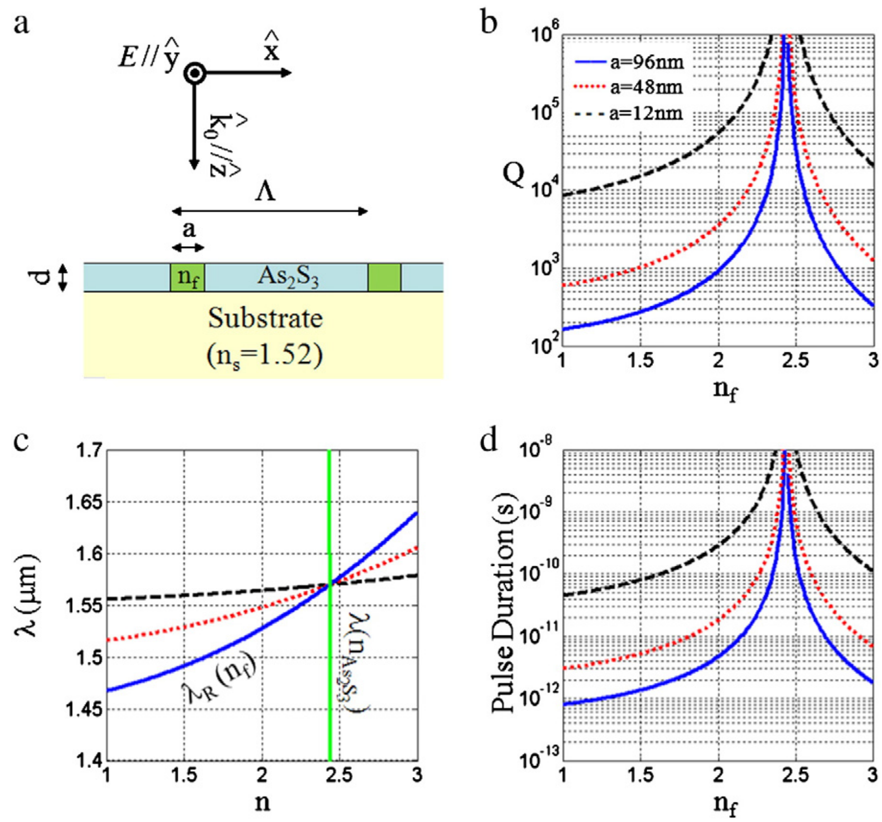

Fig. 1. (Color online) (a) Geometry: As_2S_3 grating having thickness *d = 200 nm*, period *Λ = 864 nm* and slit aperture *a*, grown on a glass substrate of refractive index $n_s = 1.52$. The slits are filled with a generic material of refractive index n_f. We consider an impinging electromagnetic wave, TE-polarized at normal incidence. (b) Q-factor of the resonances vs. n_f. when the slit aperture is a = 12 nm (dashed line), a = 48 nm (dotted line), a = 96 nm (solid line). (c) Spectral position of the Fano resonances λ_R vs. n_f, for a = 12 nm (dashed line), a = 48 nm (dotted line), a = 96 nm (solid line) and As_2S_3 dispersion curve (solid, vertical line).(d) Pulse duration needed to resolve the resonances for a Fourier limited signal.

practical technological limits to how narrow the slits can be done and a slit size *a ~ 12 nm* is at the edge of the current advanced nanofabrication techniques [8]. Here we propose a second path in order to increase the Q-factor of the resonance which is based on the filling of the slits with a material whose refractive index is closer to the refractive index of the grating. This can be accomplished by infiltrating the slits with an index matching fluid using nano-fluidic techniques [10], for example. From a physical standpoint the filling of the slits with a material whose refractive index is closer to the refractive index of the grating should be, to some degree, equivalent to having a grating with narrower slits: in both ways the leaky mode excited by the incident field according to Eq.(1) will augment its dwell time inside the grating becoming closer to the true guided mode of the unperturbed waveguide (mode-matched Fano resonance). This conjecture is indeed confirmed in Fig. 1(b) where we show how the Q-factor ($Q = \lambda/\Delta\lambda$) of the Fano resonance remarkably grows as the refractive index of the material filling the slits (n_f) gets closer and closer to the refractive index of As_2S_3 ($n_{AS2S3} \cong 2.44$ at $\lambda \sim 1.5$ μm [11]). The growing rate of Q as function of n_f is different for the three cases considered, in particular we note that the grating with wider slits needs a filling material with a refractive index closer to the refractive index of As_2S_3 in order to match the same Q of the grating with narrower slits. In Fig. 1(c) for the three cases we show the variation of the spectral position of the Fano resonances (λ_R) vs. n_f as well as the dispersion of As_2S_3 which is derived by a linear interpolation of the data reported in Ref.[11]. Note that the intersection point between all the curves in Fig. 1(c) corresponds to the condition $Q \rightarrow \infty$ in Fig. 1(b), as one may expect. Finally in Fig. 1(d) we calculate the pulse duration of a Fourier limited signal necessary to resolve these resonances. Obviously, longer pulses approaching the CW limit are necessary as $Q \rightarrow \infty$, for example at $n_f = 2.2$ and *a = 12 nm* the pulse duration necessary to resolve the corresponding resonance is *~1 ns*. In Fig. 2 we show the nonlinear response when the linear transmission is 42%, for different values of n_f, and slit aperture respectively a = 12 nm (Fig. 2(a)), a = 48 nm (Fig. 2(b)), a = 96 nm (Fig. 2(c)). In order to increase the readability of the results, in the additional material we provide an animation (see BistablePath.mov) in which we show in detail for the case with $n_f = 2.3$ of Fig. 2(a) the path that must be followed on the bistable curve for both increasing and decreasing input intensity. Similar paths apply as well to all the other curves. Consistent with our previous predictions, we observe that the input intensity necessary for the inception of the optical bistability decreases as the refractive index of the filling material gets closer and closer to that of As_2S_3. The calculation has been performed using the Fourier-modal method (FMM) [12] adapted to the nonlinear case according to the mean field theory proposed in Ref. [13]. The nonlinear refractive index of As_2S_3 has been taken according to Ref. [14] $n_2 = 2.9 {*} 10^{-18}$ m^2/W. In Fig. 3 we show the linear Fano resonances (continuous line for a = 96 nm, dotted line for a = 48 nm and dashed line for a = 12 nm) and nonlinear Fano resonances (asterisks for a = 96 nm, square for a = 48 nm and dots for a = 12 nm) with the onset of optical bistability for the three structures when the Q factor is 10^5 and the input intensities is 20 KW/cm^2. We observe that the nonlinear responses of the three structures are very close, confirming the fact that it is ruled by the Q factor, as one may expect. Moreover, we have also calculated, not shown in the figure, the switching intensities (I_s) at the center of the respective bistability regions with a result of $I_s \sim 1$ MW/cm^2 for all the three cases. From a practical perspective this means that it is possible to overcome the technical limitations that prevent the slit apertures from being too narrow and nonetheless boost the Q-

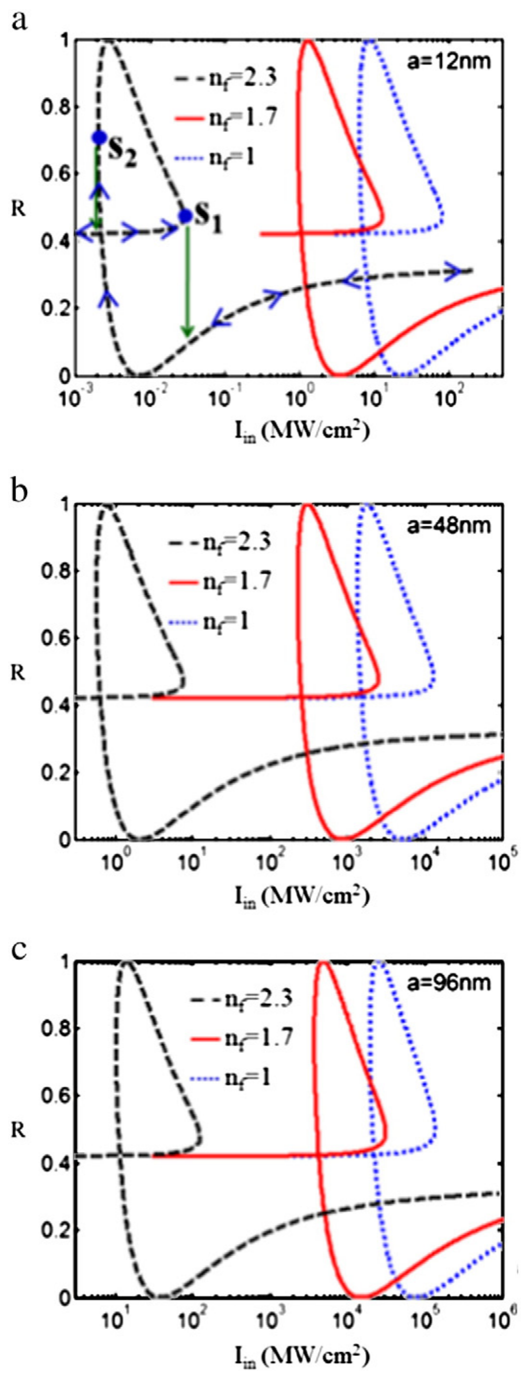

Fig. 2. (Color online) Nonlinear reflection vs. input intensity (I_{in}) for three different filling materials: $n_f = 1$ (dotted line), $n_f = 1.7$ (solid line), $n_f = 2.3$ (dashed line). The operative wavelengths have been tuned at 42% linear reflection. In Fig. 2a the slit aperture is a = 12 nm, moreover, on the curve representing the case $n_f = 2.3$, the large dots indicated with S1 and S2 and the corresponding arrows represent respectively the switching points for increasing input intensity (S1) and for decreasing input intensity (S2). In Fig. 2b the slit aperture is a = 48 nm, while in Fig. 2c is a = 96 nm.

factor by filling the slits with a material having a refractive index close to the refractive index of the grating. The threshold input intensity can be even decreased down to $I_s \sim 0.1$ MW/cm^2 and local field intensities well below the photodarkening threshold of the material [9] if we chose an operative wavelength closer to the reflection peak of the linear Fano resonance as shown in Fig. 4, although in this latter case lowering the input intensity is obtained at the expense of a reduction of the area of the hysteresis cycle. It is also interesting to observe as the hysteresis cycle approaches the optical limiting case

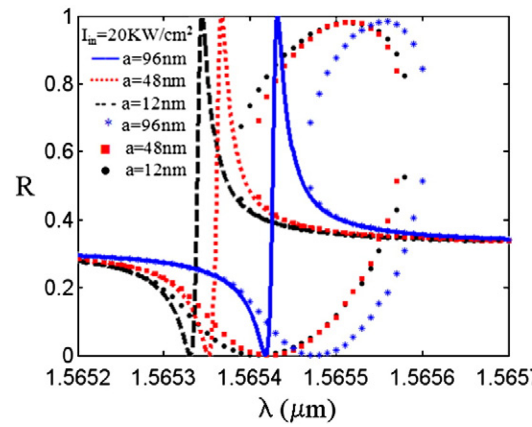

Fig. 3. (Color online) Linear Fano resonances for the reflected power (lines) and nonlinear Fano resonances (dots) with the onset of optical bistability in three cases: a = 12 nm (dashed line and circles), a = 48 nm (dotted line and squares), a = 96 nm (solid line and asterisks). The refractive index of the filling material has been chosen in each case in order to have a Q factor of 10^5.

(solid line with full circles) when the operative wavelength approaches the reflection peak of the linear Fano resonance. In this sense the optical limiting behavior of the device can be considered as the particular case of a hysteresis cycle with null area.

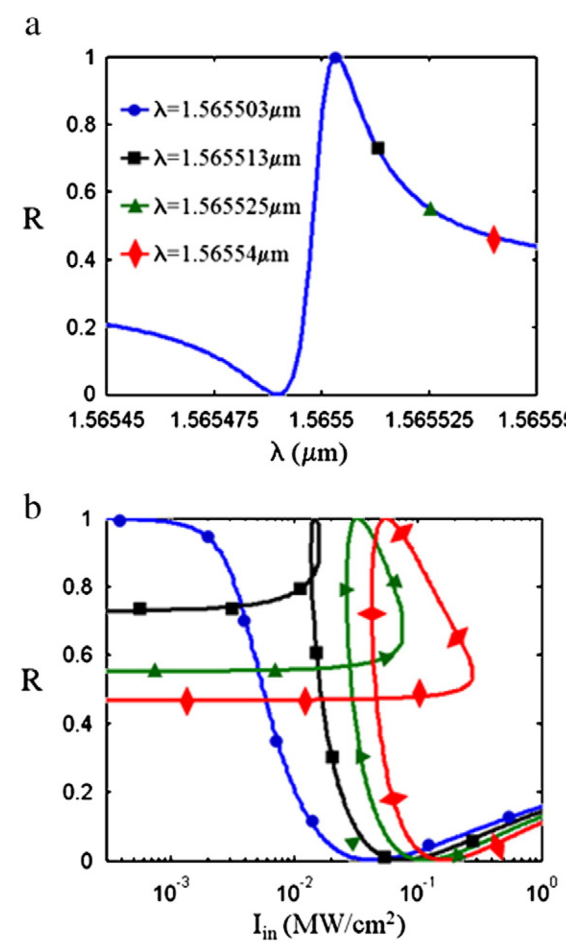

Fig. 4. Color online) (a) Linear Fano resonance of the structure having $n_f = 2.4$ and a = 96 nm. The marks on the curve indicate the operative wavelengths for the calculation reported in Fig. 4(b). (b) Nonlinear Reflection vs. input intensity (I_{in}) at different incident wavelengths as reported in Fig. 4(a).

3. Conclusions

In conclusion, we have shown that mode-matched Fano resonances can be exploited to obtain ultra-low power, all-optical switching devices. We believe that our proposed devices may nowadays be realized using advanced nano-fabrication [8] and nano-fluidic techniques [10]. Last, but not least, although here we have concentrated our attention in particular on chalcogenide materials, we would like to point out that the approach reported in this paper is quite general and can be in principle applied to any type of diffraction grating provided that the material has a cubic nonlinearity and low two-photon absorption.

Supplementary materials related to this article can be found online at doi:10.1016/j.optcom.2011.11.118.

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