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Enhanced nonlinear optics in resonant GaAs gratings: harmonic generation and optical bistability

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ABSTRACT

We present a study on nonlinear optical processes in GaAs gratings, made by perforating a single layer of GaAs with very narrow slits. Large enhancement of conversion efficiency, for both second and third harmonic generation, is predicted when a TE-polarized pump field excites the guided mode resonances of the grating. At the onset of these modes the spectrum near the pump wavelength shows abrupt changes of linear transmission and reflection that follow a typical Fano-like shape. Under these circumstances, the grating provides dramatic enhancement of local fields and fosters favorable conditions for harmonic generation processes, even in regimes of strong linear absorption at the harmonic wavelengths. In a GaAs grating pumped at 1064nm, we predict second (532nm) and third (354nm) harmonic conversion efficiencies several orders of magnitude larger than conversion rates achievable in either bulk or etalon structures made of the same material. These efficiencies are not influenced by linear absorption, and they are unrelated to grating thickness. We discuss the influence of self-phase modulation on the harmonic generation conversion efficiencies. Finally, we also analyze self phase modulation effects on resonant gratings tuning the input signal at guided mode resonances, demonstrating the possibility of triggering optical bistability at relatively low switching intensities.

Keywords: Nonlinear optics, grating, guided mode resonances

1. INTRODUCTION

Gratings are characterized by two types of Wood's anomalies: (i) the Wood-Rayleigh anomalies, associated with sharp variations of diffraction efficiencies at the onset of diffracted orders [1]; and (ii) resonance type anomalies, generated by diffracted orders phase-matched to resonant modes of the grating [2]. Guided mode resonances (GMRs) [3] belong to the latter type of anomalies. The diffraction grating obtained by modulating the index of a waveguide along its propagation direction displays abrupt changes of diffraction efficiency whenever the propagation modes of the waveguide are excited. These anomalies appear regardless of the nature of the excited modes, which may be TE or TM-polarized, and can involve surface waves, like surface plasmon polaritons in metallic gratings, or core-guided modes. When the perturbation of the waveguide is weak, spectral and angular bandwidths of the resulting resonances are usually very narrow, a few nanometers or less, making these gratings highly selective filters. We study harmonic generation and self-phase modulation effects in a 1D, free-standing, semiconductor grating with subwavelength slits using a 1064nm pump wavelength (see Figure 1(a) for a description of the structure). The grating momentum is exploited to excite TE-polarized waveguide modes that form Fano-like resonances [4] in the diffraction efficiency spectrum near the pump field wavelength. We stress that the second harmonic (SH) falls in the visible range, where linear absorption of GaAs yields an attenuation length of only 125nm, while the third harmonic (TH) falls at 354nm, where absorption lengths are even smaller (in Figure 1(b) the pump, SH and TH wavelengths are plotted along with the chromatic dispersion of GaAs). Therefore, any attempt to increase the conversion efficiency based on phase-matching techniques would fail, since the necessary homogeneous harmonic component is absorbed, leaving only the phase-locked (PL) component intact. In fact, the PL component displays the same propagation properties (absorption and phase) as the fundamental wavelength [5]. Thus, the PL component survives even if the material at the SH wavelength is characterized by huge absorption, in either bulk or cavity environments [6], provided the pump is tuned to a region of relative transparency.

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2. HARMONIC GENERATION

We begin with a linear analysis of the grating. In Figure 1(a) we show the grating and the input pump at 10° . The power of the radiated fields (pump, SH and TH) is measured in the forward and backward directions by integrating the x-component of the Poynting vector along the reflection and transmission sections, and by normalizing those values with respect to the input power per unit cell P_{inc} . In Figure 2(a) the transmission coefficient T at 10° for the pump wavelength ($\lambda_{FF}=1064\text{nm}$) is mapped as a function of the pitch P and the grating thickness W , fixing the slit size at $A=32\text{nm}$. Figure 2(b) is obtained by Figure 2(a) by cutting the map for a fixed pitch size $P=500\text{nm}$. In this map two resonant phenomena are clearly recognizable: (i) the wide resonances, whose positions are not altered by the periodicity P , are Fabry-Perot resonances due to multiple reflections at the input and output interfaces of the structure; (ii) the sharp resonances, much more dependent on P , are GMRs triggered by modes propagating along the y-direction, that is the grating periodicity axis. In this configuration, the air filling factor A/P is much smaller than one so that the slits may be considered a tiny perturbation on the smooth slab waveguide and the GMRs are well approximated by the mode of the planar structure. The phase matching condition for the excitation of GMRs is $k_{GMR} \cong k_{WM} = |k_0 \sin(\vartheta_{inc}) + 2\pi m / P|$, $m = \pm(1, 2, 3, \dots)$ where k_0 is the wave-vector of the incident plane wave, ϑ_{inc} is the angle of incidence, k_{GMR} are the GMRs' wave-vectors, $k_{WM} = k_0 n_{WM}$ are the guided modes' wave-vectors, and n_{WM} are the effective refractive indices of the guided modes supported by the slab waveguide.

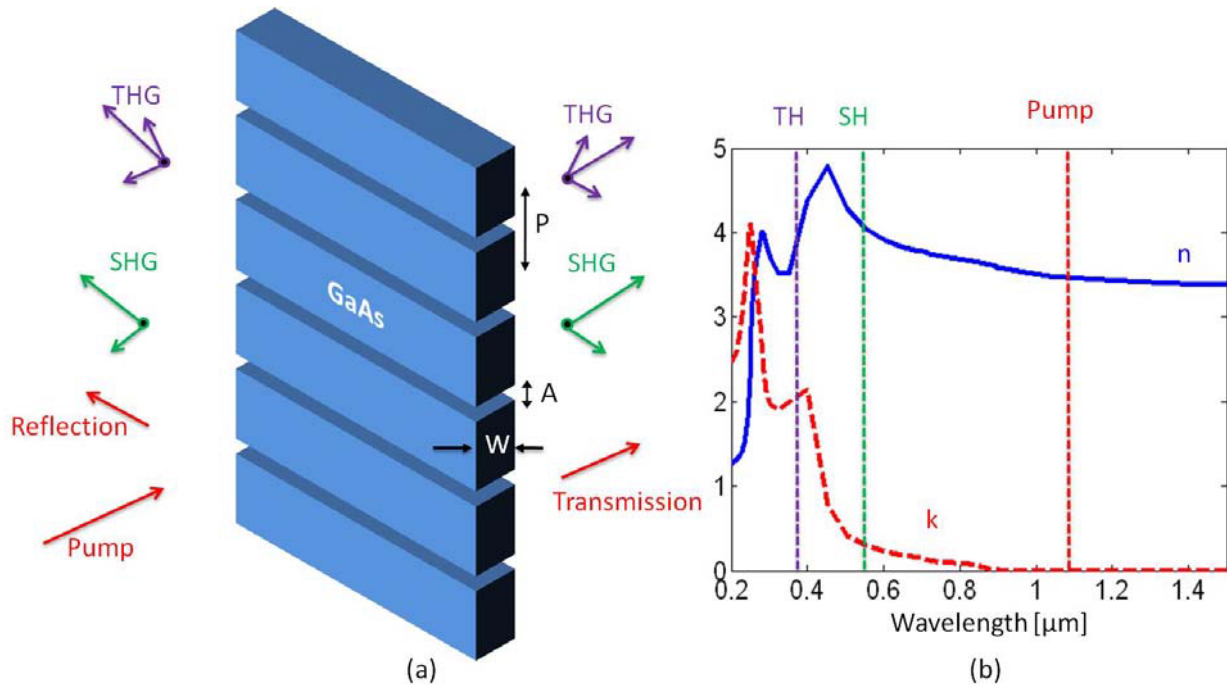


Figure 1. (a) Sketch of the GaAs grating illuminated by a pump signal incident at $\vartheta=10^\circ$. For a grating pitch $P=500\text{nm}$, the grating is subwavelength for the pump field (1064nm), while the diffracted SH is distributed on the zeroth order at $\vartheta_{0,SH}=10^\circ$ and the first order at $\vartheta_{-1,SH}=-63^\circ$. The TH is diffracted into the zeroth order, the order $m=-1$ $\vartheta_{-1,TH}=-32^\circ$ and the order $m=1$ at $\vartheta_{1,TH}=62^\circ$. The slit size is $A=32\text{nm}$, while grating pitch P and thickness W are variable. (b) Dispersion of GaAs. The pump wavelength is tuned in the transparency region of the material, while linear absorption at the SH and TH wavelengths is high.

Spectral position and field localization at the sharp GMRs can be easily predicted by calculating the dispersion of the unperturbed modes supported by the planar, slab GaAs waveguide. For example, the first couple of GMRs in Figure 2(b) (the one at $W\sim 66\text{nm}$ and $W\sim 100\text{nm}$) corresponds to the $TE_0 \pm G$ mode of the planar waveguide, where $\pm G$ is the additional grating momentum required to excite these modes with an input source at 1064nm incident at 10° . The second couple of GMRs corresponds to $TE_1 \pm G$ modes, and so on.

The nonlinear problem is solved integrating the Maxwell's equation at the pump, SH and TH wavelength with the inclusion of the following nonlinear polarization terms

$$P_{NL} = P_{\omega}^{NL} e^{j\omega t} + P_{2\omega}^{NL} e^{j2\omega t} + P_{3\omega}^{NL} e^{j3\omega t} + c.c \quad (1)$$

$$\begin{aligned} P_{\omega}^{NL} &= 2\varepsilon_0\chi^{(2)}(E_{2\omega}^*E_{3\omega} + E_{\omega}^*E_{2\omega}) + 3\varepsilon_0\chi^{(3)}\left[\left(|E_{\omega}|^2 + 2|E_{2\omega}|^2 + 2|E_{3\omega}|^2\right)E_{\omega} + E_{2\omega}^2E_{3\omega}^* + E_{\omega}^{*2}E_{3\omega}\right] \\ P_{2\omega}^{NL} &= \varepsilon_0\chi^{(2)}(E_{\omega}^2 + E_{\omega}^*E_{3\omega}) + 3\varepsilon_0\chi^{(3)}\left[\left(|E_{2\omega}|^2 + 3|E_{3\omega}|^2 + 2|E_{\omega}|^2\right)E_{2\omega} + 2E_{2\omega}^*E_{\omega}E_{3\omega}\right] \\ P_{3\omega}^{NL} &= 2\varepsilon_0\chi^{(2)}E_{\omega}E_{2\omega} + \varepsilon_0\chi^{(3)}\left[E_{\omega}^3 + 3E_{2\omega}^2E_{\omega}^* + \left(6|E_{2\omega}|^2 + 3|E_{3\omega}|^2 + 6|E_{\omega}|^2\right)E_{3\omega}\right] \end{aligned}$$

To evaluate the enhancement of nonlinear phenomena in GMRs we have compared the performances of the grating in terms of SH conversion efficiency with two reference structures: (i) a GaAs bulk (a slab of GaAs embedded in a linear medium with matching refractive index) where the interacting fields propagate only in the forward direction; (ii) a GaAs etalon surrounded by air that supports Fabry-Perot transmission resonances. We assume a TE-polarized pump field at 1064nm incident at a 10° angle to exploit the bulk quadratic susceptibility of GaAs, $\chi^{(2)}=10\text{pm/V}$, and we consider a TE-polarized SH field generated at 532nm. For the third order nonlinear susceptibility for simplicity we assume a value of $\chi^{(3)}=10^{-19}\text{m}^2/\text{V}^2$. The grating periodicity is fixed at $P=500\text{nm}$, the aperture size is $A=32\text{nm}$, while the thickness W is varied from 0 to 1 μm to excite the wide band (Fabry-Perot) resonances and sharp (GMRs) resonances of the grating. The result of this comparison is reported in Figure 3 [7], where the normalized conversion efficiency $\eta = P_{SH} / P_{FF}^2$ has been plotted for the three structures.

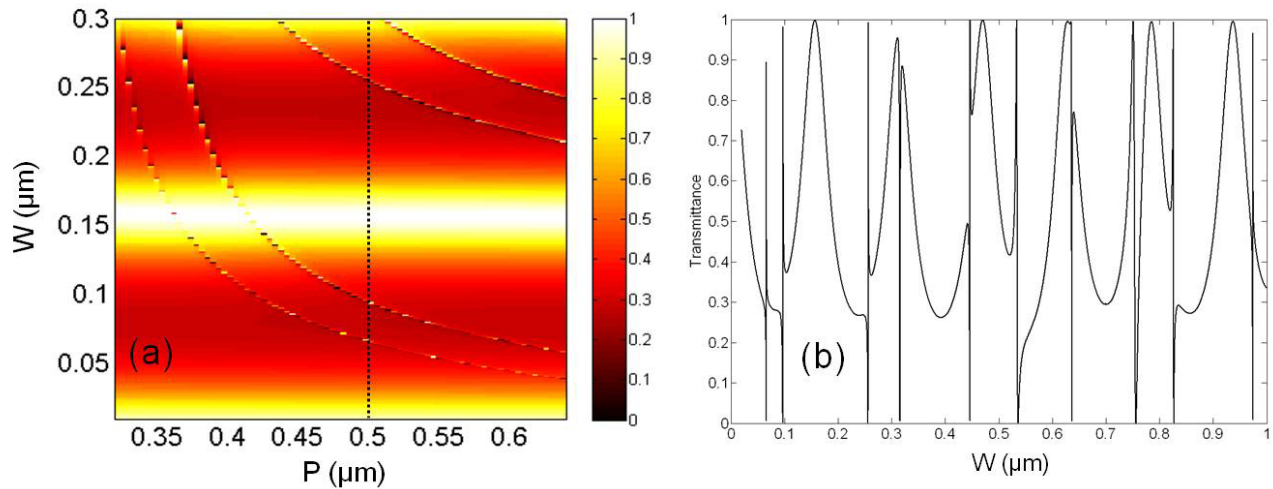


Figure 2. (a) Transmission of the GaAs grating, at $\lambda_{FF}=1064\text{nm}$ for a 10° incidence angle, as a function of the periodicity P and thickness W . (b) Linear transmittance at $\lambda_{FF}=1064\text{nm}$ for $P=500\text{nm}$ and varying the thickness W from 0 to 1 micron (following the dashed line in (a)).

In the bulk structure, the homogeneous SH component is fully absorbed in less than a coherence length $L_c = \lambda_{FF}/4(n_{FF} - n_{SH}) \sim 390\text{nm}$, where $n_{FF,SH}$ are the refractive indices at the pump and SH wavelengths, respectively. The conversion efficiency is clamped at a constant value, a condition imposed by the presence of the phase locked SH signal. In the etalon the forward SH intensity is strongly correlated to the Fabry-Perot resonances for the pump field. Even in this structure, for cavities longer than few coherence lengths, the only significant harmonic contribution comes from the PL component. The forward SHG efficiency of the grating overlaps well the etalon efficiency except when the pump signal couples to GMRs for specific grating thicknesses that yield huge conversion spikes. A closer look at Figure 3 and Figure 2(b) reveals that the nonlinear enhancement peaks correspond exactly to the abrupt, linear transmission GMRs. The enhancement comes from the strong field localization and high quality factor Q available for the pump field at the GMRs. The interesting aspect of this enhancement is that material absorption at the harmonic wavelength plays no role in the nonlinear interaction, and similar conversion rates are possible for either thin (see the peak at $W \sim 66\text{nm}$) or thick structures (see the peaks at $W > 0.5\mu\text{m}$). We observe that GaAs may be replaced with any other nonlinear material with

similar results. The results for THG are qualitatively similar to these, yielding to normalized conversion efficiencies of the order of 10^{-14} .

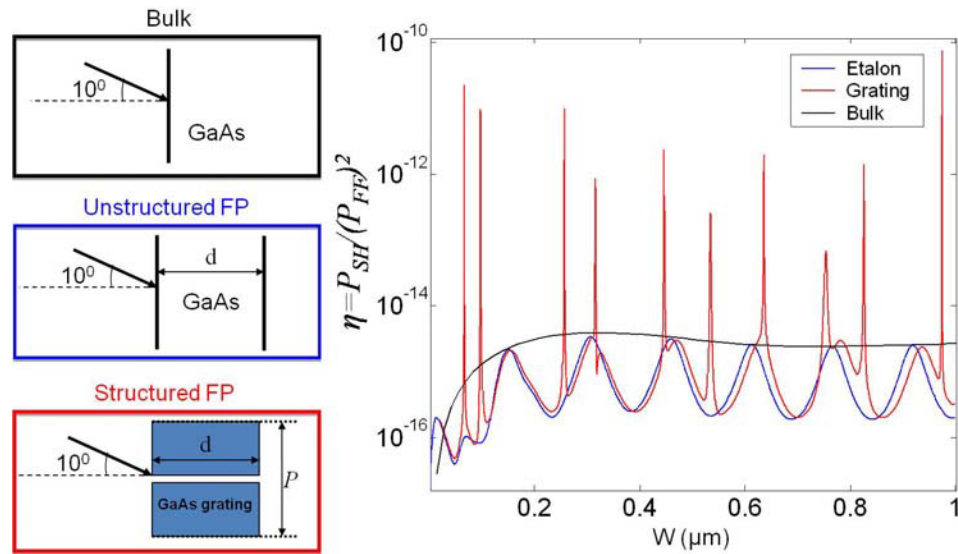


Figure 3. Normalized SH conversion efficiency of the 1D grating, the bulk and the etalon structures as a function of thickness. The three insets illustrate the three scenarios investigated.

3. SELF PHASE MODULATION AND OPTICAL BISTABILITY

In the previous calculations we used relatively small pump intensities (few kW/cm²) to avoid triggering $\chi^{(3)}$ processes, which in the presence of such narrow-band resonant states (on the order of one nanometer for some of the GMRs) may induce switching and multi-stability phenomena at low-pump-intensity thresholds. For example, in Figure 4 we report a typical scenario in which nonlinear transmission spectrum (Figure 4(a)) around the pump wavelength, as well as SHG/THG spectra (Figure 4(b)) are bent and shifted by increasing the input pump intensity. In particular, increasing the pump intensity from 1W/cm² to 20 MW/cm², the self-phase modulation induces a red shift of the pump resonance and the increased slope of this asymmetric Fano resonance results in a deformation of the harmonic spectra. An additional increase of the pump intensity will trigger a bistability in the grating, since the high transmission branch of the resonance will further red shift and eventually cross over the low transmission branch.

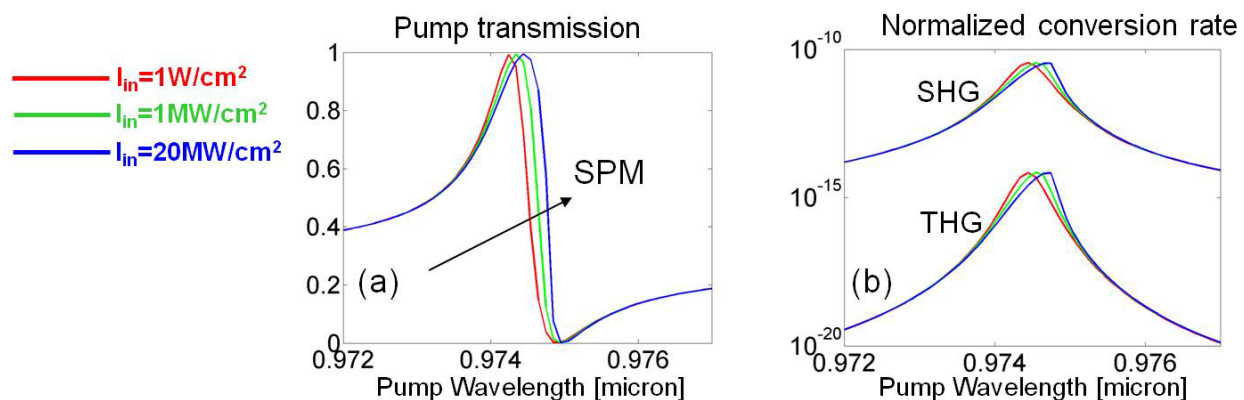


Figure 4. (a) Nonlinear transmission spectrum around the GMR of a GaAs grating with $P=440\text{nm}$, $A=32\text{nm}$ and $W=64\text{nm}$. The arrow indicates that increasing the self phase modulation (SPM) strength with the input intensity (which is varied from 1W/cm^2 to 20MW/cm^2) the resonance red-shifts and becomes steeper. (b) SHG and THG in the presence of SPM for the same input pump intensities.

All-optical switching and bistability are usually based on the Kerr-like nonlinear term $3\varepsilon_0\chi^{(3)}|E_\omega|^2$ (see the equation 1 for the nonlinear polarization term at the fundamental wavelength). The strength of this term is intensity dependent (the field intensity is $I=2\varepsilon_0cn_L|E|^2$, where n_L is the linear or low-intensity refractive index), so that tuning the pump wavelength at the GMRs of the grating will significantly boost SPM effects.

We start again from the linear behavior of the grating, fixing the periodicity at $P=440\text{nm}$ and the aperture size at $A=32\text{nm}$. In Figure 5(a) the linear transmission is plotted as a function of the input, pump wavelength and the grating thickness W . We seek for bistable phenomena in the GMRs branches, in particular on the three points (labeled I, II, and III) highlighted in the map. The linear transmission spectra at the points I and III is asymmetric, (corresponding to a grating thickness $W=80\text{nm}$ and $W=240\text{nm}$, respectively), while the spectra around point II ($W=180\text{nm}$) is symmetric, since the GMR is located in the center of the Fabry-Perot branch (high transmission in a wide-band). In the symmetric point II we find no bistability, while the asymmetric points I and III show bistability for wavelengths higher than 973nm and 1732nm , respectively.

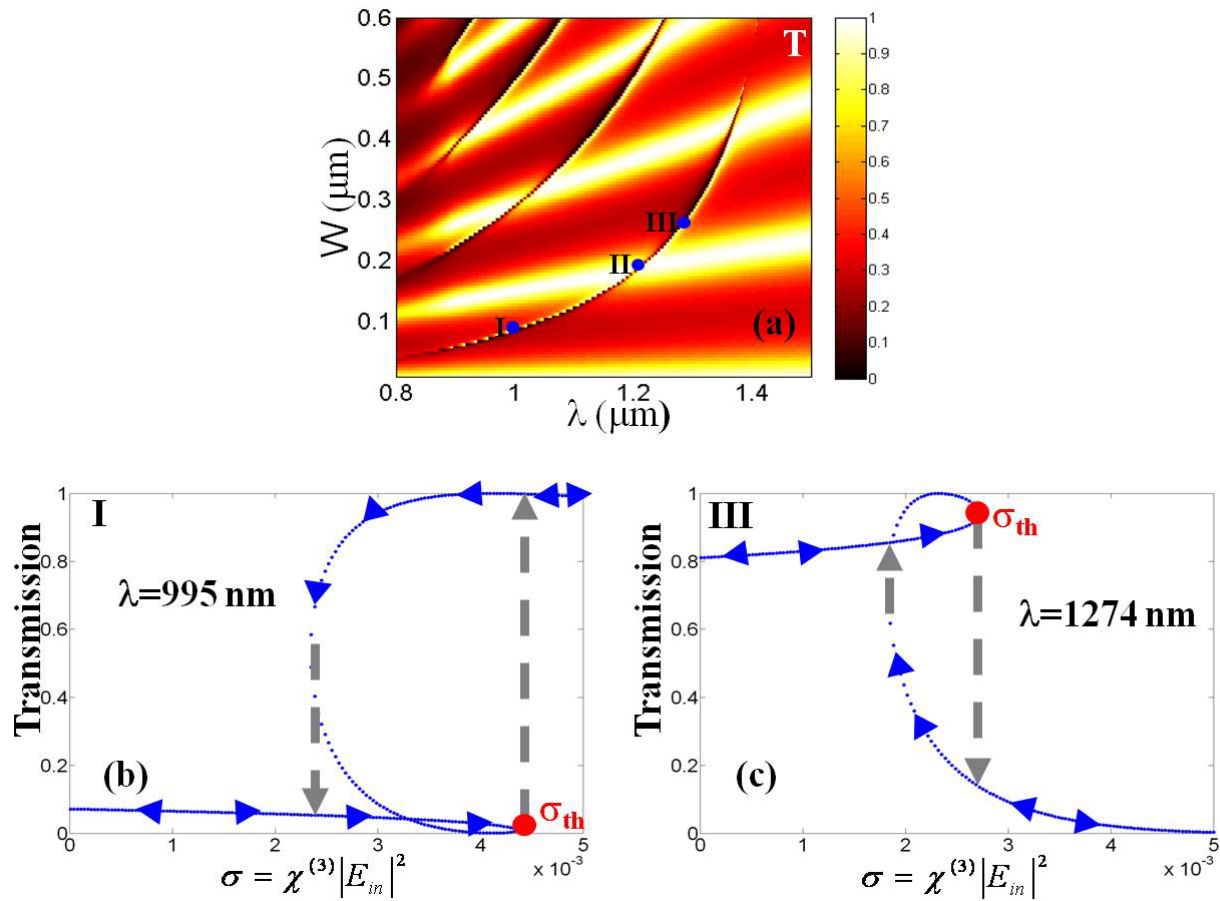


Figure 5. (a) Transmission of a GaAs grating at normal incidence as a function of the incident wavelength and the thickness W . The grating pitch is $P=440\text{nm}$ and the aperture size of the slits is $A=32\text{nm}$. (b) Bistability curve at a the wavelength 995nm at the point I of (a), where $W=80\text{nm}$. (c) Same as in (b) for the point III, where $W=240\text{nm}$. σ_{th} is the switching threshold.

In Figure 5(b) and (c) we report the bistability curves for the points I and III, fixing the wavelength at 995nm for I and 1274nm for III, and varying increasing the adimensional parameter σ , which is the nonlinear susceptibility multiplied by the electric field intensity. For point I ($W=80\text{nm}$) the transmission goes from a low state to a high state when $\sigma \sim 4.2$ (red circle and grey up-arrow in Figure 5(b)), while it goes back to a low state decreasing σ down to ~ 2.5 . A narrower hysteresis loop is found at the point III ($W=240\text{nm}$), where nonlinear transmission switches from a high state to a low state for $\sigma \sim 2.8$ (see the red circle and the grey down-arrow in Figure 5(c)). The switching intensities corresponding to

these values of σ are on the order of few tens of MW/cm^2 . The performance of the switch strictly depends on the quality factor of the GMR, which can be easily improved for instance by considering smaller apertures (or A/P ratios) [8].

4. CONCLUSIONS

In conclusion, we have demonstrated drastically enhanced nonlinear phenomena in 1D GaAs gratings with subwavelength slits. The coupling of the pump field to GMRs introduces sharp, Fano-like resonances where strong field localization and enhancement take place, leading to the prediction of harmonic conversion efficiencies that are several orders of magnitude larger than bulk or etalon structures. Thanks to the PL SH component the efficiency is not influenced by linear absorption at the harmonic wavelengths, and is unrelated to grating thickness or to the order of the guided mode excited. Moreover, by exploiting the same field enhancement and confinement effects of GMRs, we have demonstrated that optical bistability can be achieved at relatively low intensities tuning the pump wavelength in the neighborhood of asymmetric GMRs. We emphasize the generality of our approach that does not rely in particular on the use of GaAs, but can be in principle applied to any diffraction grating provided that the material possesses low absorption at the pump wavelength.

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