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Phase-Locked Second Harmonic Generation in GaAs nanocavities

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Abstract. We theoretically study light propagation through sub-wavelength apertures on a silver substrate filled with GaAs, in the enhanced transmission regime. We predict enhanced conversion efficiencies even under high absorption conditions.

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1. Introduction

During the last few decades several groups have pointed out the existence of a double peak structure in the second harmonic generation (SHG) process under phase and group velocity mismatch conditions. This trapping process has been demonstrated to be produced by the inhomogeneous term solution of the wave equation at the interface between a linear and a nonlinear medium [1-4]. The evidence for this phenomenon can be found in several experimental works, where the large phase mismatch between the fundamental and the second harmonic waves allows the observation of two distinct SH pulses travelling at different phase and group velocities [5-7]. As recently shown, this peculiar behavior can also be interpreted as a phase-locking mechanism that remains valid also for negative index [8] or absorbing materials [9, 10] thanks to a trapping and dragging mechanism between the fundamental and phase-locked generated pulse [6-10]. It has also been demonstrated that sub-wavelength apertures carved on metal substrates lead to an enhanced linear response [11], and that surface waves and cavity effects are simultaneously important also in nonlinear processes [12]. In this paper we combine the resonant behavior of these structures with the phase locking mechanism to study nonlinear wave propagation including second and third harmonic generation in wavelength shorter than the band edge, where the nonlinear optical coefficients may be unusually high (i.e. GaAs and or GaP in the visible and UV regimes).

2. Linear response of a single sub-wavelength slit on Silver substrate and the enhanced nonlinear response

For simplicity we consider a silver [13] layer having thickness w and a single aperture of size a , which has been filled with GaAs. A necessary and sufficient condition for phase locked harmonic generation to occur in the absorption region is that the pump itself be tuned to a region of transparency. By tuning the pump at $\lambda = 1064\text{nm}$ we have $\epsilon(1064)_{\text{GaAs}} \sim 12.10 + i0$. Both second (532nm) and third (354nm) harmonic wavelengths are tuned deep in the absorbing regions and no harmonic generation is expected. Nevertheless, as already shown in the case of planar Fabry-Perot cavities, our calculations show the generation of SH and TH fields phase locked to the pump [10] that resonate inside the nano-cavity. In order to maximize the linear response at $\lambda = 1064\text{nm}$ we varied the thickness of the substrate and aperture size and obtained a transmission map that clearly reveals the strong resonant nature of the structure (see Fig.1). We thus sought to enhance the nonlinear response that we previously reported on similarly resonant but empty sub-wavelength structures [12]. We simulated a single 60nm-lit carved on a silver substrate of variable depth filled with GaAs. We performed our simulations by assuming a $d_{14} = d_{25} = d_{36} = 50 \text{ pm/V}$ [14], an incident TM-polarized incident pump signal having peak intensity $I_0 = 2 \text{ GW/cm}^2$. The mere assumption that the metal is nonlinear via Coulomb and Lorentz contributions [12] makes it possible to generate both TE- and TM-polarized harmonic fields, as Fig.2 demonstrates. These fields are generated even under high-absorption conditions, and survive thanks to a phase locking mechanism that sets in between the pump and its harmonics.

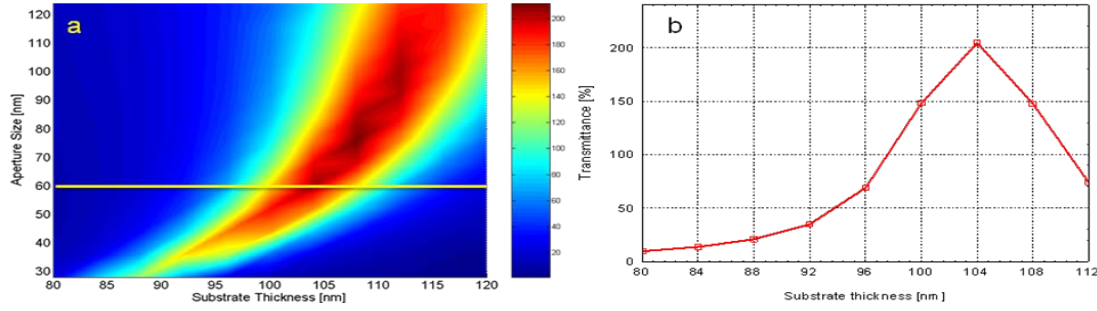


Fig.1. (a) Transmission map @ $\lambda=1064\text{nm}$ for a single slit carved on a silver substrate, filled with a material having $\epsilon_x=12.10+i0$. The maximum for the transmission is obtained for a 76nm aperture carved on a 104 nm substrate ($T = 212\%$). (b) Transmittance vs. Substrate thickness for a slit 60nm wide, and corresponds to tracing the yellow line in Fig.1a.

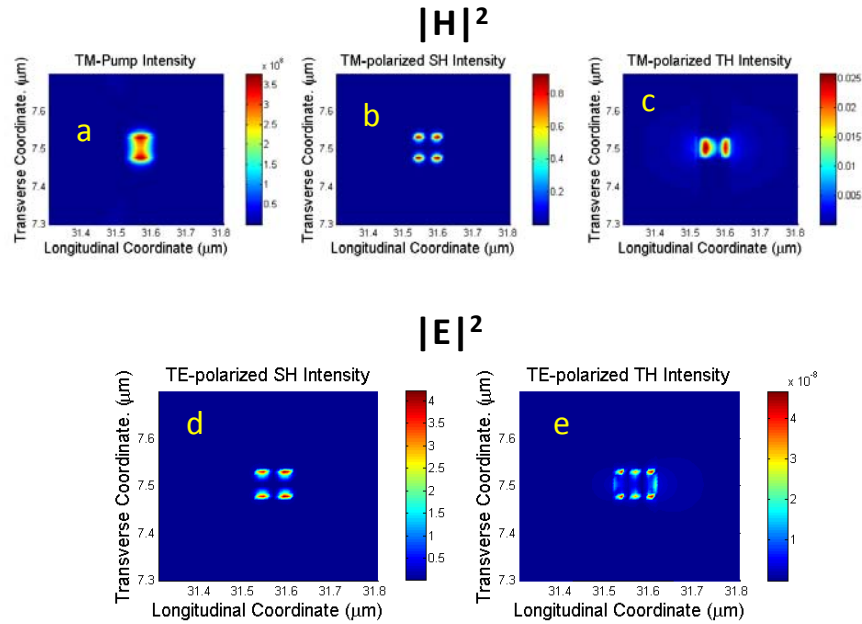


Fig.2: TM-polarized incident pump (a), SH (b) and TH (c) Magnetic intensity profiles; TE-polarized SH (d) and TH (e) electric field intensities inside the 60nm wide by 104nm long nano-cavity.

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