Effect of two-photon absorption on Kerr-nonlinear resonator behaviour

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The Kerr-nonlinear effect shows large potential for ultrafast all-optical signal processing and may be of great importance for future optical communication systems. A major limitation to its applicability is however the existence of two-photon absorption. This has already been discussed in literature for a homogeneous structure. In this paper, the effect of two-photon absorption on the operation of Kerr-nonlinear resonators is studied and the applicability of standard semiconductor systems for all-optical nonlinear switching is evaluated.

Introduction

As discussed in [1, 2], the use of resonating structures greatly reduces the optical power and device length required for all-optical signal processing. This is obtained by confining the light inside the resonator and by slowing down the pulse propagation.

As its intrinsic counterpart, two-photon absorption (2PA) is one of the major limitations to the applicability of Kerr-nonlinear phenomena. In the case of resonating structures, two-photon absorption is enhanced by the same mechanisms - optical confinement and slow waving - as the Kerr effect. Furthermore, due to the influence of 2PA on the optical power level, the achievable Kerr-nonlinear interaction inside the resonator is reduced and thus the required optical power for all-optical processing increases.

Resonator structure

The resonator structure that will be discussed, is the following

$$h_{\frac{\lambda_c}{8}}\, l_{\frac{\lambda_c}{4}} h_{\frac{\lambda_c}{4}} l_{\frac{\lambda_c}{4}} \ldots l_{\frac{\lambda_c}{4}} h_{N_{cav}.\frac{\lambda_c}{2}}\, l_{\frac{\lambda_c}{4}} h_{\frac{\lambda_c}{4}} l_{\frac{\lambda_c}{4}} \ldots l_{\frac{\lambda_c}{4}} h_{\frac{\lambda_c}{8}}$$

with h resp. l indicating the higher resp. lower index material, N_{dbr} the number of l-layers in one resonator period, N_{cav} a integer number and λ_c a chosen center resonance wavelength. The mirror and cavity part can be easily recognized.

2PA effect on transmission, reflection and loss

In contrast to structures such as simple waveguides, resonator structures (except for ring resonators) have both forward and backward propagation field components. As a result, it is impossible to solve the wave equation of such structures in the presence of two-photon absorption strictly analytically (by using e.g. a multi-time scale approach or perturbation theory). Therefore, simulations will be required to determine the remaining parameter dependences. In this section, the effect of 2PA will be studied on the resonance transmission, reflection and loss of the structure defined in the previous section.

The total transmission, reflection and loss of any structure are always related by the following equation,

$$|t_{tot}(\nu)|^2 + |r_{tot}(\nu)|^2 + A_{tot}(\nu) = 1 \tag{1}$$

with $t_{tot}(\nu)$ resp. $r_{tot}(\nu)$ the total field transmission resp. reflection and $A_{tot}(\nu)$ the total loss of the structure. Furthermore, one has

$$(|t_{tot}(\nu_c)|^2 - |r_{tot}(\nu_c)|^2)^2 - 2(|t_{tot}(\nu_c)|^2 + |r_{tot}(\nu_c)|^2) + 1 \approx 0 \tag{2}$$

with ν_c the resonance frequency. This equation was not derived analytically, but obtained through fitting of simulation results. In this way, both the resonance transmission and reflection can be expressed in terms of the total 2PA induced loss $A_{tot}(\nu_c)$,

$$|t_{tot}(\nu_c)|^2 = \frac{1}{2}\left(1 - A_{tot}(\nu_c) + \sqrt{1 - 2A_{tot}(\nu_c)}\right) \tag{3}$$

$$|r_{tot}(\nu_c)|^2 = \frac{1}{2}\left(1 - A_{tot}(\nu_c) - \sqrt{1 - 2A_{tot}(\nu_c)}\right) \tag{4}$$

To determine this nonlinear loss, the following method is used. For small intensities, the loss due to two-photon absorption is equivalent to the phase shift at resonance induced by the Kerr effect,

$$A_{tot} \propto 2K_2 |E_{in}|^2 \Leftrightarrow \Delta\phi \propto n_2 |E_{in}|^2$$

with $K_2 = \frac{c}{4\pi\nu}\beta$ the nonlinear extinction coefficient, β the two-photon absorption coefficient, n_2 the Kerr coefficient and E_{in} the input field. This relation represents the refractive index - absorption coefficient duality. The factor 2 is due to the fact that loss is related to the optical intensity, whereas the phase is related to the optical field. This resonance phase shift has been determined analytically by the authors in [1] and is given by,

$$\Delta\phi_c = \frac{3\pi}{8}\left(\frac{n_h}{n_l}\right)^{2N_{dbr}} \frac{n_2}{n_h} |E_{in}|^2 \left(N_{cav} + \frac{n_h^4 + n_l^4}{n_h^4 - n_l^4}\right) \tag{5}$$

with n_h resp. n_l the linear high resp. low refractive indices. In this way, one has for low intensities,

$$A_{tot,low}(\nu_c) = \frac{3}{16}\lambda_c \left(\frac{n_h}{n_l}\right)^{2N_{dbr}} \frac{\beta}{n_h} |E_{in}|^2 \left(N_{cav} + \frac{n_h^4 + n_l^4}{n_h^4 - n_l^4}\right) \tag{6}$$

For general electric fields, it was obtained by simulation that,

$$A_{tot}(\nu_c) \approx |t_{tot}(\nu_c)|^4 A_{tot,low}(\nu_c) \tag{7}$$

This $|t_{tot}(\nu_c)|^4$ instead of $|t_{tot}(\nu_c)|^2$ is unexpected and could not yet be explained. Using equation (3), one obtains the following implicit formula for the total loss,

$$A_{tot}(\nu_c) = \frac{3}{64}\left(1 - A_{tot}(\nu_c) + \sqrt{1 - 2A_{tot}(\nu_c)}\right)^2 \lambda_c \left(\frac{n_h}{n_l}\right)^{2N_{dbr}} \frac{\beta}{n_h} |E_{in}|^2 \left(N_{cav} + \frac{n_h^4 + n_l^4}{n_h^4 - n_l^4}\right) \tag{8}$$

Effect of 2PA on nonlinear operation

Resonator-based all-optical functionalities are typically related to the shift of the resonance frequency $\Delta\nu_c$, which is for small intensities related to the phase shift $\Delta\phi$ [1],

$$\Delta\nu_c = \frac{\Delta\nu}{2}\Delta\phi \tag{9}$$

with $\Delta\nu$ the resonance bandwidth of the resonator given by,

$$\Delta\nu = \frac{4\nu_c \left|t_{dbr}\right|^2_{\nu_c}}{\pi\left((1+\left|r_{dbr}\right|^2_{\nu_c})(2N_{cav}-1)+2\left|r_{dbr}\right|_{\nu_c}\frac{n_h+n_l}{n_h-n_l}\right)} \tag{10}$$

In the presence of absorption, the resonance shift is in good approximation a factor $|t_{tot}(\nu_c)|^2$ less, which represents the relative loss in power, so

$$\Delta\nu_{c,2PA} \approx |t_{tot}(\nu_c)|^2 \Delta\nu_{c,lossless} \tag{11}$$

Using, equations (3), (5), (9) and (11), equation (8) can be rewritten as,

$$FOM = \frac{|t_{tot}(\nu_c)|}{2\pi(1-|t_{tot}(\nu_c)|)}\frac{\Delta\nu_{c,2PA}}{\Delta\nu} \tag{12}$$

with $FOM = \frac{n_2}{\lambda_c\beta}$ the figure of merit for Kerr-nonlinear materials. Using this equation, one can calculate the remaining transmitted power for a material system with a certain FOM as a function of the relative resonance shift. This is shown in Fig.1 for $FOM = \frac{1}{3}, 1, 3$.

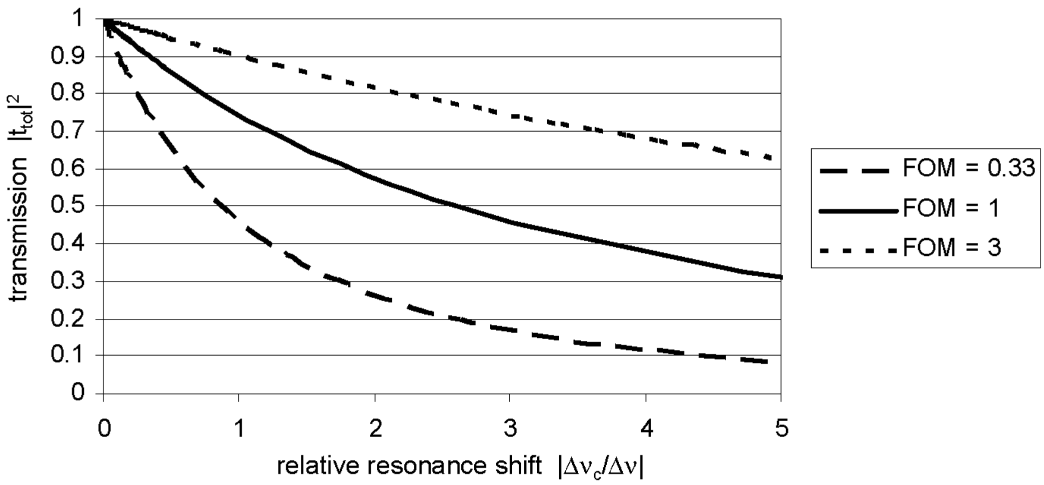

Figure 1: Transmission as a function of relative resonance shift for different FOM.

For reasonable nonlinear operation, a relative resonance shift of $\frac{\Delta\nu_{c,2PA}}{\Delta\nu} = 1$ should be obtainable with a transmission $|t_{tot}(\nu_c)|^2 > 0.5$. Using equation (12), this corresponds to a figure of merit of,

$$FOM \geq 0.385 \tag{13}$$

For standard, ultrafast, Kerr-nonlinear semiconductor materials such as *AlGaAs* and *Si*, the FOM value at the telecom wavelength $\lambda = 1.55\mu m$ [3, 4] is,

$$FOM_{AlGaAs} \approx 5.38 \tag{14}$$
$$FOM_{Si} \approx 0.37 \tag{15}$$

which makes *AlGaAs* an excellent and *Si* still a reasonable material voor resonator-based Kerr-nonlinear functionalities

Conclusion

The effect of two-photon absorption on resonator-based Kerr-nonlinear all-optical functionalities was discussed analytically. The obtained equations allow to derive a FOM value to achieve nonlinear operation with acceptable loss. At the telecom wavelength $\lambda = 1.55\mu m$, this condition is easily met by the *AlGaAs* material system, while *Si* is still acceptable.

Acknowledgements

Part of this work was performed in the context of the Belgian DWTC IAP-PHOTON project. Gino Priem thanks the Flemish Fund for Scientific Research (FWO-Vlaanderen) for a doctoral fellowship.

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