Effect of loss mechanisms on Kerr-nonlinear resonator behaviour

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Abstract: The degradation of Kerr-nonlinear behaviour in resonating structures due to optical loss is investigated. From this, the feasibility of ultrafast, Kerr-nonlinear operation is derived for the AlGaAs and Si material system.

OCIS codes: (190.7110) Ultrafast nonlinear optics; (190.3270) Kerr effect

1 Introduction

Optical loss mechanisms have a significant impact on the achievement of Kerr-nonlinear operation of resonating structures.

Ideally, the use of these structures greatly reduces the optical power and device length required for all-optical signal processing such as phase shifting [1]. This is due to the confinement of the light inside the resonator and the slowing down of the pulse propagation, which enhance the Kerr-nonlinear interaction. The obtained change in refractive index inside the resonator causes the resonance wavelength to shift in proportion to the input power. An example of this is shown in figure 1.

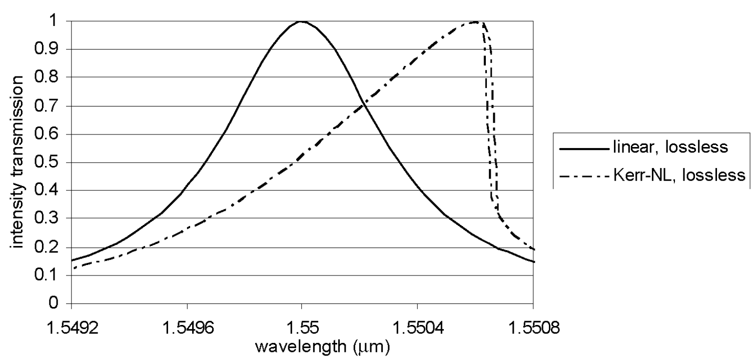


Fig. 1. Example of resonator-based Kerr-nonlinear operation. The shift of each wavelength is proportional to the input power and the transmission. For higher input power, a bistable region can occur, which is the case here.

Next to phase shifting, also other types of signal processing are possible, such as all-optical switching and bistability (see figure 1) [2].

In practice however, structures like ring resonators and photonic crystal resonators are much more critical to fabricate than simple waveguides and suffer from additional loss mechanisms such as radiation and scattering loss. Furthermore, two-photon absorption (2PA) - as intrinsic counterpart of the Kerr effect - is also present. In these resonating structures, the two-photon absorption effect is enhanced by the same principle - optical confinement and slow waving - as the Kerr effect. In this paper, the impact of these loss components is evaluated.

2 Impact of different loss mechanisms

Linear loss mechanisms such as radiation and scattering loss can typically be modelled as single-photon absorption (1PA). Their effect is equal for both the linear and nonlinear operation. The mean consequences of this type of loss are a decrease of the resonance transmission and a higher resonator bandwidth. As a result, a higher input power is required to obtain the same resonance shift.

The effect of two-photon absorption (2PA) is quite similar to that of 1PA mechanisms. An important difference is however the fact that 2PA only affects the Kerr-nonlinear behaviour, while linear loss also has an effect on linear behaviour of the resonator. This is shown in figure 2.

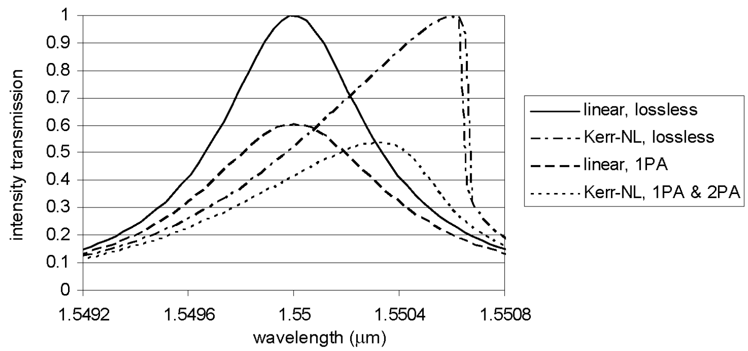


Fig. 2. Example of resonator-based Kerr-nonlinear operation in the presence of 1PA and 2PA loss. Due to 2PA, the lossy nonlinear transmission is lower than the lossy linear one.

Significant two-photon absorption can therefore severely degrade the nonlinear potential of a structure. High linear loss on the other hand will only have an impact on the required power level for ultrafast nonlinear operation.

3 Semiconductor Kerr-nonlinear systems

Two of the most interesting semiconductor materials for ultrafast, Kerr-nonlinear operation are the AlGaAs and Si system. Around the telecom wavelength of $\lambda = 1.55\mu m$, they have a nonlinear figure of merit value of [3, 4]

$$FOM_{AlGaAs} \approx 5.38 \tag{1}$$

$$FOM_{Si} \approx 0.37 \tag{2}$$

with $FOM = \frac{n_2}{\lambda\beta}$ (n_2 is the Kerr and β the 2PA coefficient).

In order to have reasonable all-optical (stable) switching [2], a resonance shift $\Delta\lambda_c = \frac{4\sqrt{3}}{9}\Delta\lambda_{BW}$ with $\Delta\lambda_{BW}$ the resonator bandwidth should be possible with acceptable asymmetric distortion due to 2PA (see also above). This shift is the maximum resonance shift without introducing bistability.

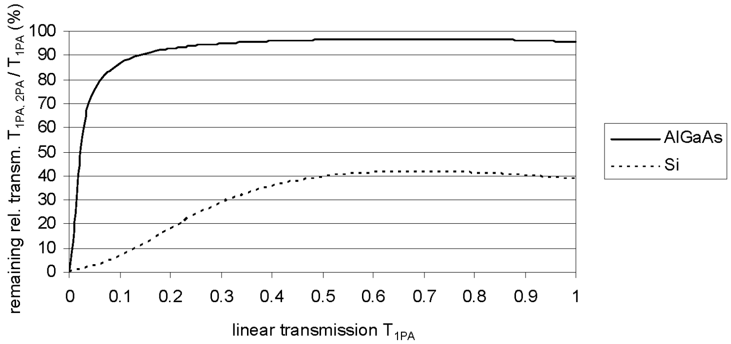


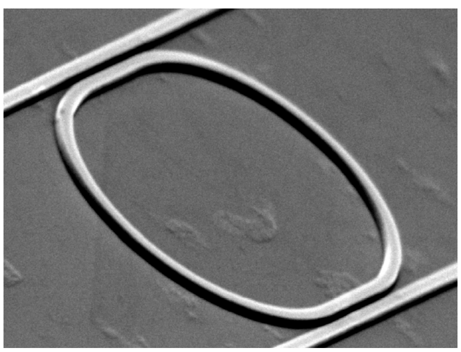
Fig. 3. Remaining nonlinear transmission as a function of the linear transmission for both AlGaAs and Si for a resonance shift of $\Delta\lambda_c = \frac{4\sqrt{3}}{9}\Delta\lambda_{BW}$.

To evaluate this criterion for the given material systems and to allow practical device analysis, a analytical Kerr-nonlinear resonator model including both 1PA and 2PA effects has been derived. The results are shown in figure 3. In this figure, the remaining nonlinear peak transmission taking into account both 1PA and 2PA $T_{1PA,2PA}$ (relative to the linear peak transmission T_{1PA} - i.e. with only 1PA) is plotted as a function of the linear peak transmission for the mentioned resonance shift.

As can be seen, the effect of 2PA is quite severe in the case of Si and is only acceptable for very low linear losses. For the AlGaAs system, the impact of 2PA is very limited, even for low linear transmissions. The RMS error on this curve is approximately 2%.

4 Practical example

This theory is now used to predict the potential of a realistic structure - i.e. a racetrack resonator in Silicon-On-Insulator (figure 4(a)) [5]. The thickness of the Silicon layer is $220nm$. The radius and the length of the coupling section of the resonator are respectively $5\mu m$ and $3\mu m$. The width of the racetrack and the coupling section is $450nm$. The measured transmission diagram is shown in figure 4(b), together with the fitted linear and nonlinear transmission curves. The nonlinear transmission has been verified by simulations.



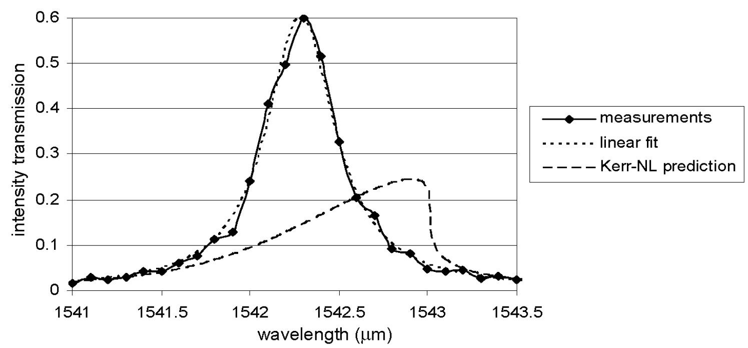


Fig. 4. (a) Racetrack resonator made in Silicon-On-Insulator. (b) Measured and fitted linear spectrum. The predicted nonlinear operation is also shown.

As predicted in the previous section, the impact of 2PA in a Silicon system is quite severe. In this example, only $\frac{T_{1PA,2PA}}{T_{1PA}} \approx 40.5\%$ of the linearly transmitted power remains, which is on the limit of acceptability. A similar structure in AlGaAs on the other hand would allow a transmitted fraction of 97.8%.

5 Conclusion

The effect of optical loss - and in particular two-photon absorption - on Kerr-nonlinear resonator operation has been discussed. At $1.55\mu m$, this effect is quite significant in a Silicon based system, but always negligible in AlGaAs. Practical devices are however realisable.

References

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