# Resonator-based all-optical phase shifting in pump-probe configuration

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*Resonator structures show great potential for improving ultrafast, nonlinear data processing and provide new functionalities - such as limiting and bistability - which cannot be realised with simple, homogeneous components. When operated in a pump-probe configuration, the signal processing possibilities are extended to multiple channels, however at the expense of a higher power level, which is related to the channel spacing. In this paper, all-optical phase shifting is discussed in the case of a pump-probe set-up and the advantages and disadvantages compared to a single signal approach are investigated.*

## Introduction

The optical Kerr effect in standard semiconductor materials is an ultrafast, but also very small effect ($n_2 \approx 10^{-13} - 10^{-15} cm^2/W$), which typically leads to the requirement of high input powers or long devices for practical applications. Resonating structures enhance the effect by confining the optical power and slowing down the propagation of the pulse. On the other hand, the introduction of resonator structures limits the obtainable signal bandwidth and therefore, a trade-off between both of these implications must be made.

This trade-off has been studied in detail by the authors in previous papers in the case of a single data signal (which was operated either in a linear or nonlinear regime), both for all-optical phase shifting [1, 2] and all-optical switching applications [2]. In contrast to this single-signal operation, a pump-probe set-up allows to control more than one (linear) data signal - separated from the pump frequency by a periodic spacing (Free Spectral Range) - by means of a single nonlinear pump signal. This is discussed here for the case of all-optical phase shifting.

## Linear and nonlinear properties of the used resonator structure

The resonator structure that is used, has the following period,

$$h_{\frac{\lambda_{c,0}}{8}} \; l_{\frac{\lambda_{c,0}}{4}} h_{\frac{\lambda_{c,0}}{4}} l_{\frac{\lambda_{c,0}}{4}} \ldots l_{\frac{\lambda_{c,0}}{4}} h_{N_{cav}.\frac{\lambda_{c,0}}{2}} \; l_{\frac{\lambda_{c,0}}{4}} h_{\frac{\lambda_{c,0}}{4}} l_{\frac{\lambda_{c,0}}{4}} \ldots l_{\frac{\lambda_{c,0}}{4}} h_{\frac{\lambda_{c,0}}{8}}$$

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 $\lambda_{c,0}$ a chosen center resonance wavelength. The mirror and cavity part can be easily recognized. Any multiple of this structure has a transmission of 1 at the resonance frequency $\nu_c$. In general, it will take more than one resonator to achieve a certain phase shift.

The Free Spectral Range of this structure can be derived from the results of [2] by means of the transfer matrix method and is given by,

$$FSR = \frac{\nu_c}{cav - \frac{1}{2} + \frac{|r_{dbr}|_{\nu_c}}{2}\frac{n_h+n_l}{n_h-n_l}} \tag{1}$$

with $n_h$ resp. $n_l$ the linear higher resp. lower refractive index and $|r_{dbr}|_{\nu_c} = \frac{n_h^{N_{dbr}} - n_l^{N_{dbr}}}{n_h^{N_{dbr}} + n_l^{N_{dbr}}}$ the field reflectivity of the resonator mirrors. The resonance bandwidth $\Delta\nu$ is equal to

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

with $|t_{dbr}|_{\nu_c} = \sqrt{1-|r_{dbr}|^2_{\nu_c}}$ the field transmittivity of the mirror sections.

In Refs. [1, 2], the phase shift per period $|\Delta\phi|_0$ due to a nonlinear signal (i.e. the pump) around the center resonance wavelength $\lambda_{c,0}$ was calculated to be,

$$|\Delta\phi|_{c,0} \approx 2\left|\frac{\Delta\nu_{c,0}}{\Delta\nu}\right| \tag{3}$$

with the center resonance frequency shift $\Delta\nu_{c,0}$ given by,

$$\Delta\nu_{c,0} \approx -\frac{3}{4}\left(\frac{n_h}{n_l}\right)^{N_{dbr}}\frac{n_2}{n_h}\,|E_{in}|^2\,\nu_c\frac{N_{cav}+\frac{n_h^4+n_l^4}{n_h^4-n_l^4}}{N_{cav}+\frac{n_l}{n_h-n_l}} \tag{4}$$

with $n_2$ the Kerr coefficient of both the higher and lower index material and $E_{in}$ the incoming electric field.

The resonance shift of other resonance frequencies $\nu_{c,n} = \nu_{c,0} + n.FSR$ with $n = \pm1, \pm2, ...$ is smaller than $\Delta\nu_{c,0}$ and approximately given by,

$$\Delta\nu_{c,n} \approx \frac{2}{3}\Delta\nu_{c,0} \tag{5}$$

for practical FSRs. This can be understood as follows: at resonance, the pump beam produces an almost standing wave inside the resonator cavity ($\left|E_{p,cav}\right|^2\cos^2(z)$-like intensity profile with $z$ the propagation axis and $\left|E_{p,cav}\right|$ the field amplitude), which gives rise to a $\left|E_{p,cav}\right|^2\cos^2(z)$-like index profile due to the optical Kerr effect. The field propagation effect felt by the pump beam due to this corrugation inside the cavity is then, using a multi-time scale approach [1] ,

$$E_{p,cav}(z) \propto \left|E_{p,cav}\right| cos(z)\exp\left(-j\frac{2\pi\nu}{c}\frac{3}{4}n_2\left|E_{p,cav}\right|^2 z\right) \tag{6}$$

On the other hand, based on the average index profile, one would expect the propagation effect to be only,

$$E_{p,cav}(z) \propto \left|E_{p,cav}\right| cos(z)\exp\left(-j\frac{2\pi\nu}{c}\frac{1}{2}n_2\left|E_{p,cav}\right|^2 z\right) \tag{7}$$

since $\langle cos^2(z) \rangle = \frac{1}{2}$.

Based on this, it can be concluded that the propagation effect and therefore the resonance shift is not only due to an average change in the refractive index, but it is further enhanced due to the corrugated profile. For frequencies far from the pump frequency, this corrugation does not anymore work constructively. As a result, only the average effect remains, resulting in equation (7). The associated phase shift is then equal to,

$$|\Delta\phi|_{c,n} \approx \frac{2}{3}|\Delta\phi|_{c,0} \qquad (8)$$

## Design of π-phase shifting device

For practical purposes, a phase shift of π should be realized for a reasonable input field and total device length. In the single-signal case, this phase shift could be obtained for input fields $|E_{in}| < 200kV/cm$ (or input intensities $I_{in} < 0.15GW/cm^2$) and device lengths $L_{tot} < 1mm$, which is much better than the results obtainable without resonators. However, it was also observed that the achievable improvement is largely limited by the signal bandwidth. A trade-off had to be made since a large signal bandwidth and small $E_{in}$ conflict with a large $\Delta\phi$ and thus a small $L_{tot}$ With the values above, bandwidths up to $100GHz$ could be obtained [1, 2].

In the case of a pump-probe configuration, an additional parameter comes into play. Not only the signal bandwidth $\Delta\nu_s$, but also the signal spacing (or the Free Spectral Range) $FSR$ will be of importance for the obtainable improvement. To compare different data signals on an equal basis, the $FSR$ is expressed with respect to $\Delta\nu_s$ as,

$$FSR = f_{FSR}\Delta\nu_s \qquad (9)$$

with a fixed value for $f_{FSR}$. In this way, the same amount of information per $Hz$ is compared. Indeed,

$$\frac{\Delta\nu_s}{FSR} = \frac{1}{f_{FSR}} \equiv constant \qquad (10)$$

This is done in Fig. 1 for a realistic structure: $n_h = 2.6$, $n_l = 2.34$ (thus a corrugation of $\approx 10\%$ and $n_2 = 0.6 \times 10^{-13} cm^2/W$ (or $2.4 \times 10^{-16} cm^2/V^2$). $f_{FSR}$ is taken to be 20. The number of mirror layers, the cavity length and the number of resonators are optimized with respect to the total device length by means of the analytical results presented above. The required input field and device length is also shown for the case without resonators. In the latter case, the device length needed to achieve a phase shift of π would be about $1cm$ for a pump input field $|E_{in}| \approx 550kV/cm$ (or input intensity $I_{in} \approx 1GW/cm^2$). This means that resonators give rise to interesting improvements for the purpose of phase shifting.

However, as can be seen in Fig. 1, for the purpose of all-optical phase shifting, it is best to use as few channels as possible (the higher $\Delta\nu_s$, the higher the possible improvement). Furthermore, the obtainable improvement factor is much less than possible in the case of

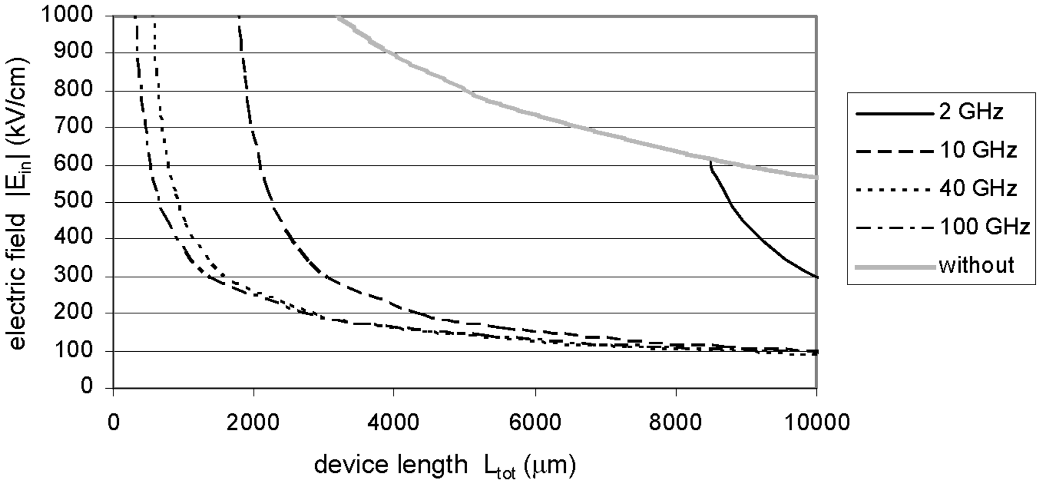


Figure 1: Trade-off between pump input field $|E_{in}|$ and device length $L_{tot}$ for several signal bandwidths $\Delta\nu_s$. The required field in the case without resonators (homogeneous structure) is also shown.

a single signal. In the latter, improvements in device length of the order 1000 – 10000 were possible depending on the signal bandwidth, while here improvements of a factor 1 – 10 can be achieved.

## Conclusion

The pump-probe set-up of nonlinear Kerr effect resonator structures was explained analytically and excellent agreement with simulation results was obtained. In this configuration, the requirements for all-optical phase shifting are still considerably reduced, however much less than in the case of a single-signal approach. The obtainable improvement is the highest when data is split over only a few channels.

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## References

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