Nonlinear behaviour in nanophotonic structures for ultrafast signal processing

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Promoters: G. Morthier, R. Baets

Abstract— **A very promising way to overcome the speed limitations of electronics is using the ultrafast capabilities of nonlinear optics. In this domain, light pulses are used to control other light pulses. To reduce the power requirements, ultrasmall waveguides and resonating structures must be applied.**

First, different types of nonlinear interactions were investigated theoretically to evaluate potential applications and limitations. Afterwards, these results were verified experimentally using nanophotonic ring resonators fabricated in Silicon-on-Insulator, confirming the feasibility of several nonlinear effects for ultrafast data processing.

Keywords—**nonlinear optics, nanophotonics, telecommunication**

I. Introduction

NONLINEAR optics describes a wide variety of effects which are dependent on the intensity of the light. Several of these nonlinear interactions - such as the optical Kerr effect and two-photon absorption - have very short response times (order fs). This makes them very appropriate for high bit-rate data communication. On the other hand, these effects are also typically very weak so that high optical powers or long devices are required.

A possible solution is using nanophotonic structures like compact waveguides and resonator structures (Fig. 1), which enhance the optical field en slow down the propagation of the light. In this way, the nonlinear interaction is amplified, however at the cost of usable signal bandwidth. As a result, a trade-off between speed and power is necessary.

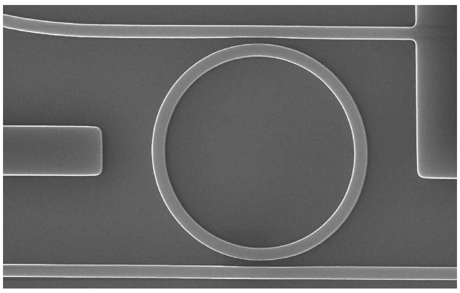

Fig. 1. Ring resonator coupled to two photonic wires. The width of these waveguides is only 500 nm, while the radius of the ring resonator is 4 μm. Inside the resonator, the light can enhanced be enhanced by a factor of more than 100.

II. Theoretical study

To investigate this trade-off, an analytical model was constituted, allowing the evaluation of the impact of different parameters on the nonlinear behaviour of the resonator structures (Fig. 2). In addition, this model allows to design and optimize different nonlinear functional components in a very time-saving way in contrast to many numerical programs [1], [2].

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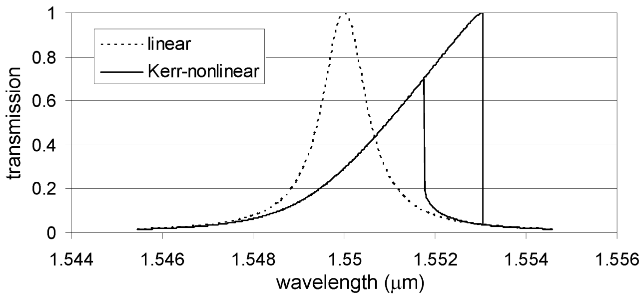

Fig. 2. Impact of the Kerr effect on the transmission spectrum of a ring resonator. In the nonlinear regime, the resonance wavelength changes and the spectrum becomes asymmetrical, giving rise to new effects like optical bistability with potential as memory operation.

With this theoretical model, it is also possible to evaluate the usability of different semiconductor materials. For the case of the Kerr effect, the most appropriate 'standard' semiconductor system at $1.55 \mu m$ was found to be AlGaAs. For two-photon absorption, Silicon is a very suitable material. The use of a high-contrast material system is however required to obtain the optimum nonlinear interaction. With the aid of new material systems, such as InP nanocrystals, this interaction may be further enhanced at the expense of additional complexity.

III. Design and fabrication

In the high-contrast material system Silicon-on-Insulator (SOI), different waveguide devices and resonator types were designed to verify the theoretical results experimentally. The fabrication of these test components occurs in association with the Interuniversity MicroElectronics Center (IMEC) at Leuven. The structure patterns are defined in a resist layer using a deep UV lithography stepper, after which a dry etching process transfers the patterns into the Silicon layer. A detailed overview of the processing steps can be found in [3]. These processes are in se CMOS processes, characterized and adapted for the fabrication of nanophotonic circuits, allowing production on industrial scale.

IV. Experimental verification

In cooperation with the National Institute of Information and Communications Technology (NICT) of Tokyo, pulsed nonlinear measurements were made onto different types of photonic wires. Ultrafast, all-optical switching based on two-photon absorption has already been demonstrated with bit-rates up to 80

Gb/s [4]. Good agreement with the theoretical results was obtained.

On the ring resonators, both continuous-wave and pulsed measurements were done. Two-photon absorption was again observed, however not as dominant effect: derived phenomena such as free-carrier dispersion and thermal heating dominate the nonlinear behaviour. These refractive index effects are much stronger than the Kerr effect, but also much slower. However, due to the compactness of the ring structures, their response time is still much faster than in conventional devices.

The continuous-wave measurements demonstrate that (thermal) optical bistability could be obtained with only ≈ 300 mW (Fig. 3). These results could be explained by adding carrier and temperature effects to the theoretical model. A carrier lifetime of about 1 ns and a temperature relaxation time of about 100 ns were derived [5].

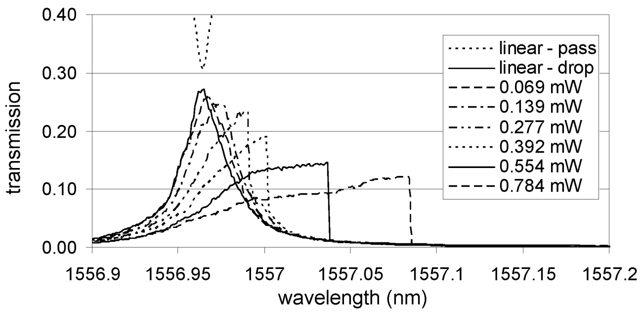

Fig. 3. Transmission spectrum for different input powers. Two-photon absorption reduces the resonance transmission, while free-carrier and thermal dispersion shift the resonance wavelength to higher wavelengths.

In addition, quasi-periodic pulsating behaviour was observed for the higher input powers due to interaction between the carrier and thermal effect [5]. The origin of these pulsations lies in the fact that both effects are counterproductive with different time constants, making the resonance wavelength fluctuate around a center position instead of converging to a stable situation. This is visible on the measurements by e.g. plotting the standard deviation on the top of the average detected power (Fig. 4). The quasi-periodic nature of these oscillations is due to noise in the input power. Stabilizing these pulsations could result in a new type of ns pulsed lasers with short repetition rate.

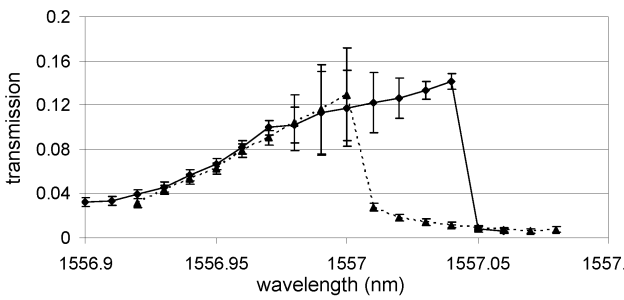

Fig. 4. Instabilities of the transmission spectrum indicated by the large standard deviations of the detected power. The instabilities correspond to quasi-periodic pulsations, which - if stabilized - could be using for ns pulsed lasers with short repetition rate.

Pulsed measurements demonstrated the potential of the free-carrier dispersion effect for ns signal processing. Using a high-power pulsed pump signal, a continuous-wave probe signal at a nearby resonance wavelength was modulated at a speed of 0.5 Gb/s (Fig. 5). At this speed, the thermal effects that are present, are averaged and only influence the relative position of the resonance wavelength. Adding an external temperature controller would result in a completely tunable building block for all-optical signal processing at Gb/s speed. Higher bit rates could be obtained by reducing the carrier lifetime, however at the cost of higher pump power.

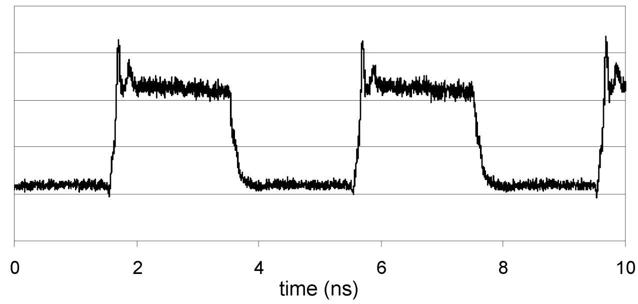

Fig. 5. Example of measured probe signal at the output of a ring resonator. The continuous wave probe signal at the input is being modulated by a pulsed pump signal by means of carrier effects inside the resonator.

V. Conclusions

The potential of ultrafast nonlinear optics was investigated both theoretically and experimentally. Highly confined structures - such as wires and resonators in high-contrast material systems - provide the opportunity of $\geq$ 100 Gb/s all-optical signal processing at modest power levels. In addition, secondary phenomena like carrier and thermal effects can be used for slower operation at even lower power levels. New materials systems may even further reduce the requirements for nonlinear operation.

Acknowledgments

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