Toward a miniature optical true-time delay line

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A millimeter-sized photonic crystal waveguide and better understanding of fabrication imperfections may lead to microwave signal processing on a chip.

Microwave signals are used in wireless communications, satellite links, and radar, and they enable countless and widespread applications such as cell-phones, remote sensing, and imaging. The ability to control or shift the microwave phase is essential for processing signals, but it is not easy to achieve. Phased-arrayed antennas in particular require a true-time delay, such that a broadband microwave signal experiences a phase-shift which is proportional to the frequency. Moreover, this delay needs to be tunable. That is very difficult to obtain using electronic circuits, but it is very easy using photonics, namely an optical wave carrying the microwave signal through an optical fiber.

A variable delay can be readily achieved by controlling the wavelength of the optical carrier, due to the fiber dispersion (the dependence of group velocity on wavelength). However, about 100m of fiber is required in order to change the delay by approximately 100ps. Squeezing that amount of dispersion into a single photonic integrated circuit would enable an extremely compact high-performance device for microwave processing. We have demonstrated that photonic crystal (PhC) technology is a viable way to realize this.

Because of their inherently small footprint, PhCs are naturally suited for integrating complex architectures. They offer very strong controllable dispersion that also enables the miniaturization of photonic devices such as an electro-optical modulator. However, propagation of light in PhC is particularly sensitive to fabrication imperfections, resulting in disorder-induced scattering. Furthermore, that effect is enhanced as the group velocity is decreased. State-of-the-art microelectronics processing facilities are able to produce very high quality semiconductor PhCs, but it is also crucial to understand the complex and subtle connection with signal propagation. We have developed a low-loss, high-quality PhC technology on membranes based on gallium indium phosphide (GaInP), which as a III-V semiconductor enables optical amplification. We demonstrated optical nanocavities with a quality factor of more than 1 million, which can be taken as a benchmark of the fabrication quality. Moreover, by greatly reducing coupling losses, we have made a PhC waveguide with total insertion losses (from fiber to fiber) smaller than 10dB. An SEM image of a GaInP PhC waveguide termination with integrated mode-adaptor is shown in Figure 1.

We used a measurement technique based on low-coherence interferometry and proper filtering to generate maps that represent the transmitted (or reflected) signal of the PhC waveguide as a function of the wavelength and delay. The map in Figure 2 (left) reveals the change of the relative propagation delay for wavelengths of 1520–1580nm. Structural disorder scatters light from the propagating mode out of plane, to other modes, or backwards to the same mode: see Figure 1 (bottom). This latter effect becomes dominant as the group velocity is

Figure 1. Scanning electron microscope image of a photonic crystal waveguide with integrated mode-adaptor that reduces coupling loss to ~1dB.

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In long waveguides, the probability of multiple scattering events (light being scattered back and forth in the waveguide) becomes significant, even for moderately slow light. As a consequence, resonances appear, corresponding to light remaining in the waveguide for longer time. This is visible in the maps in Figure 2 (left) and corresponds to the speckle-like pattern following the leading front of the transmitted signal.

We have introduced a new formalism to modeling coherent scattering. We combined coupled mode theory and a fully 3D description of disorder scattering theory to provide a quantitative evaluation of transmission in a disordered PhC waveguide without fitting parameters. Figure 2 (right) shows the calculated map revealing an excellent agreement with the experiment. This new tool enables us to take fabrication imperfections into account for ab-initio design of waveguides.

Figure 3 shows a typical scheme of a micro-wave photonic link based on our PhC delay line. The S-parameter (S21) of the device is measured with a vector network analyzer in the 1–20GHz range. The relative radio frequency phase change is shown as a function of the wavelength, revealing almost flat curves (which are the signature of true-time delay). The corresponding optical delay varies from 20 to about 100ps resulting in an 80ps delay swing.

In conclusion, a tunable true-time delay line can be implemented in PhCs. Better understanding and modeling of disorder effects enables ab-initio design of optimized structures. That will be crucial for our next step, the implementation of complex microwave processing functions on a single PhC chip.

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References