Enlarging the scope of possibility in nonlinear silicon photonics

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Spectacular progress in silicon-based light technology raises the question whether its usefulness can be extended to include energy harvesting and midwave-IR applications.

The mushrooming of silicon photonics over the past decade has proved it to be one of the most active disciplines within the field of integrated optics. The rapid pace of progress is made possible, in particular, by exploiting nonlinear optical effects in silicon. This capability has led to Raman amplification and lasing, efficient broadband wavelength conversion, supercontinuum generation, and so forth. The question today is no longer whether silicon can exhibit nonlinear optical effects, but rather how well and how much further we can reach. To this end, our group has been focusing on exploring new branches of nonlinear optical effects in silicon and the niche applications enabled by these phenomena, some of which we highlight here.

We previously demonstrated a two-photon photovoltaic (TPPV) effect,1 which reduces optical loss by two-photon absorption (TPA) and free-carrier absorption (FCA), and serendipitously converts the optical energy lost to TPA to useful electrical power. The harvested power can be recycled to supply electrical power to electronics on the same silicon chip. Beyond optical interconnects, another possible application is photovoltaic power converters (PPCs) and optically powered sensors for fiber data links. These advances will lead the way to green, integrated photonics, which could have a profound effect on the telecommunications industry.

Beyond the near-IR (NIR) regime, silicon turns out to be a very attractive optical material for midwave-IR (MWIR) applications because of the absence of TPA and its associated FCA losses in this region, unsurpassed crystal quality, high thermal conductivity, and excellent damage threshold. We first demonstrated MWIR Raman amplification in silicon at 3.4 μm,2 and proposed to use it in optical-image preamplification based on Talbot self-imaging in a multimode waveguide (i.e., the image is periodically repeated at regular distances along the waveguide) for image-sensing applications.3 This proof of concept, together with its excellent material properties, makes silicon an appealing material choice for realizing MWIR laser sources and amplifiers, for example, in biochemical sensing and detection in both medical and military applications, and laser ranging and detection.

Although bulk silicon has a centrosymmetric crystal structure that prevents second-order $\chi^{(2)}$ nonlinearity, perturbation of crystal symmetry gets around the limitation by applying nonhomogeneous mechanical stress (strain gradient) to the crystal. Based on recent work on strained silicon that shows a linear electro-optic effect,5 we recently proposed a new concept: periodically poled silicon (PePSi).6 PePSi creates alternating

Figure 1. Example of a periodically poled silicon (PePSi) waveguide formed by covering a silicon channel waveguide with two types of silicon nitride (SiN)-stressed films at regular intervals along the waveguide: one induces compressive and the other tensile stress. (b) Simulated output spectra of quasi-phase-matched difference-frequency generation in a 2 cm-long PePSi waveguide (period ∼ 8 μm): a 12ps pump pulse at 1.3 μm (input peak intensity = 1.5 GW/cm²), a 12ps signal pulse at 1.75 μm (input peak intensity = 12.5 M W/cm²), and an idler at 5.1 μm.

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stress gradients along a silicon waveguide using a periodic arrangement of stressed cladding films (see Figure 1). The structure creates appreciable $\chi^{(2)}$ and simultaneously achieves quasi-phase matching (QPM). Based on previously reported $\chi^{(2)}$ values, our simulations have shown efficient MWIR generation (~5μm) through the quasi-phase-matched difference-frequency-generation process (QPM-DFG). The PePSi concept is meant to broaden the capabilities of silicon as a nonlinear optical medium.

Naturally, silicon has a narrow Raman gain linewidth, which restricts the bandwidth of silicon Raman amplifiers and limits their practical application. In contrast to the recent pioneering experiments of broadband parametric gain based on phase-matched four-wave mixing in silicon waveguides, we recently demonstrated Raman scattering with simultaneous continuum generation in a silicon waveguide to produce broadband Raman gain that is significantly larger than silicon’s natural Raman linewidth: see Figure 2(a). This achievement is realized using a pulsed pump source that is modified by self-phase modulation (SPM) within a silicon waveguide. The tandem actions of the free-carrier effect and Kerr nonlinearity (a third-order nonlinearity arising from a bound-electron contribution resulting in intensity-dependent changes in the refractive index). Using the same approach, we can also achieve broadband wavelength conversion through coherent anti-Stokes Raman scattering (CARS), another Raman effect that generates coherent radiation with upshifted Stokes frequency (rather than downshifted, as in the case of Raman scattering) with respect to the pump frequency: see Figure 2(b). The Raman process enables broadband Raman amplification or CARS wavelength conversion without the need for any phase matching. We also discovered that varying the pulse characteristics (i.e., pulse power, chirp, duration, and timing) makes it possible to produce a broadened gain spectrum with a tailored profile in silicon.

Last but not least, we recently showed, for the first time, that the Raman effect can also produce optical loss through so-called inverse Raman scattering (IRS). In this nonlinear process, light at the anti-Stokes wavelength is attenuated in the presence of an intense pump light in the silicon waveguide: see Figure 3(a). Our experiments show more than 15dB resonant attenuation in the anti-Stokes spectrum in the presence of an intense pump light in the silicon waveguide:

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see Figure 3(b). To the best of our knowledge, IRS has never been observed in a semiconductor medium. Interestingly, our numerical simulation also reveals that FCA, which generally degrades the performance of silicon devices, facilitates observation of IRS. IRS could prove to be a valuable tool for photonic-signal processing of high-bandwidth radio-frequency signals—such as performing subtraction of two intensity-modulated signals—because power is fundamentally a positive quantity. IRS is also an important complementary tool to Raman gain and wavelength conversion through stimulated Raman scattering and CARS.

The phenomena described here could provide invaluable insight into the field of nonlinear silicon photonics. They also offer avenues to new classes of active silicon photonic devices, especially for use beyond optical interconnect applications, such as optically powered sensors for data links using the TPPV effect.

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References