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Broadband optical amplification on a silicon chip

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Four-wave mixing can be used to design on-chip amplifiers with unprecedented bandwidth and low power.

Chip-scale photonics are becoming increasingly promising for replacing some of the copper interconnects in conventional microelectronic chips for applications that require low power and high bandwidth. Several components compatible with current silicon microelectronics have already been demonstrated, such as highly compact electro-optic modulators,[1] all-optical switches,[2] low-loss waveguides, and filters.

A critical component that remains to be developed is an on-chip amplifier. Although the indirect bandgap of silicon has made it difficult to create such an amplifier based on stimulated emission, researchers have recently exploited the large effective optical nonlinearities of silicon to produce an alternative amplification mechanism. The first demonstration of the use of a nonlinear process to produce amplification was based on the Raman effect.[3] However, the Raman bandwidth over which amplification occurs is relatively narrow, which prevents its use in wavelength-division-multiplexing systems that require gain at least over tens of nanometers.

We have recently demonstrated broadband amplification over 30nm by using another nonlinear process known as four-wave mixing (FWM).[4] Previous demonstrations of amplification using this phenomenon, for example in fibers,[5] required either high pump powers or long interaction lengths, which made them very difficult to integrate into a compact chip-scale structure. By careful engineering of Si-waveguide structures, we have been able to greatly enhance the FWM efficiency such that signal amplification can be achieved in centimeter-long devices with modest pump powers.

In a solid-state material such as Si, FWM is due to the third-order nonlinear susceptibility: that is, the polarization of the material contains a contribution that depends on the cube of the electric-field. Although such a nonlinearity can lead to a number of optical processes, we focus on the FWM process in which two photons at frequency ω_p from a pump wave are converted to a signal wave at frequency ω_s and an idler wave at frequency ω_i. For the case in which pump and signal waves are injected into a medium, the interaction between the the two leads to amplification of the signal and to the generation of a third wave, the idler. This process must however, satisfy energy conservation such that $2\omega_p = \omega_s + \omega_i$. In addition, for this photon conversion to occur efficiently and perhaps lead to amplification of the signal, it must satisfy momentum conservation, which means that the propagation constants k_p, k_s, and k_i for the pump, signal, and idler waves respectively, must satisfy the condition $2k_p = k_s + k_i$. When this condition is satisfied, the nonlinear optical process is said to be phase-matched.

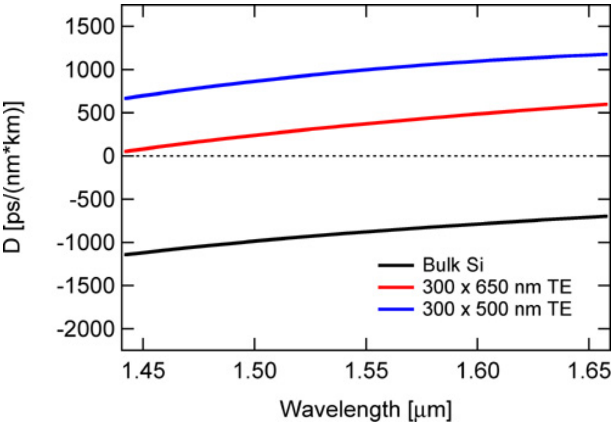

Figure 1. *Plots of the group-velocity dispersion of bulk silicon (black) and of two silicon waveguides with anomalous dispersion (red and blue) are shown above. By controlling the shape and size of the waveguide, the dispersion can be made anomalous ($D > 0$).*

In general, there are two contributions to the propagation constants that must be considered to achieve phase matching. The first is the dispersion of the material, which results in a wavelength-dependent refractive index and which generally introduces a phase mismatch. The second contribution, known as phase modulation, arises from the same nonlinearity that

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gives rise to the FWM process and causes the pump wave to modify the propagation constants of the signal and idler wave twice as much as it modifies itself. Ultimately, the key to achieving phase matching and amplification is the appropriate balance of the dispersion and nonlinear contributions. This can only occur when the group-velocity dispersion (GVD) parameter D is positive, i.e., anomalous. It is defined as $D = -\lambda_p(d^2n_p/d\lambda^2)/c$, where n_p and λ_p are the index of refraction and wavelength of the pump wave.

For silicon photonic structures, it is not immediately obvious that this balance can be achieved. Figure 1 shows a plot of D for bulk silicon over wavelengths in the telecommunication regime. It can be seen that it it is large and negative (i.e, normal) across the entire regime (black line). However, for ultra-high confined guided waves, there is an additional source of GVD, known as waveguide dispersion, that can overcome the large negative contribution of the bulk material. Thus, the same confinement that produces large effective nonlinearities in silicon can also be used to tailor the dispersion properties for enhancing the FWM process and producing amplification. Figure 1 also plots the GVD for two different sized waveguides (blue and red lines), showing that a net positive D can be achieved and that small changes in the waveguide dimensions can tune D to produce the desired dispersion characteristics. We fabricated such waveguides using conventional microelectronic processes and verified that we could indeed produce broad regimes of anomalous GVD over the telecommunication bands.[6] Figure 2 compares the predicted FWM gain as a function of frequency for pump fields in the normal (black line) and the anomalous (red and blue lines) dispersion regimes. It is clear that large gain is only possible in the anomalous dispersion regime. For fixed pump power, it is possible to tailor the bandwidth over which amplification occurs by varying dispersion, which can be done by tuning the waveguide dimensions.

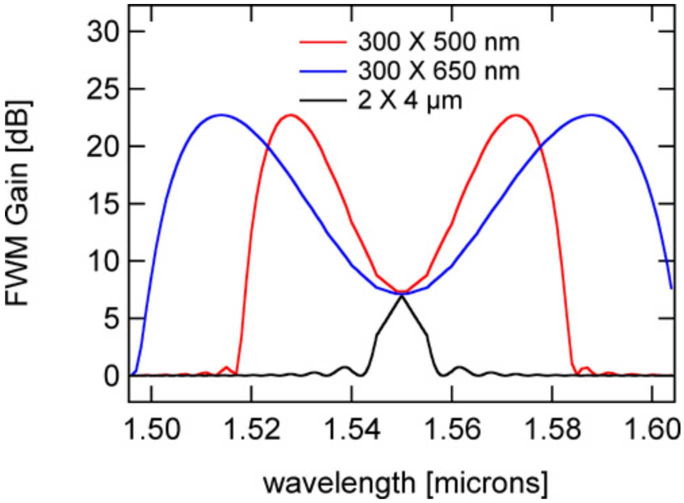

Figure 2. *Theoretically predicted plots of the four-wave mixing gain for various silicon waveguide transverse dimensions. For the 2×4μm waveguide (black), the group-velocity dispersion (GVD) is normal (D > 0), whereas for the 300×500nm (red) and 300×650nm (blue) waveguides, the GVD is anomalous and large broadband amplification can be achieved.*

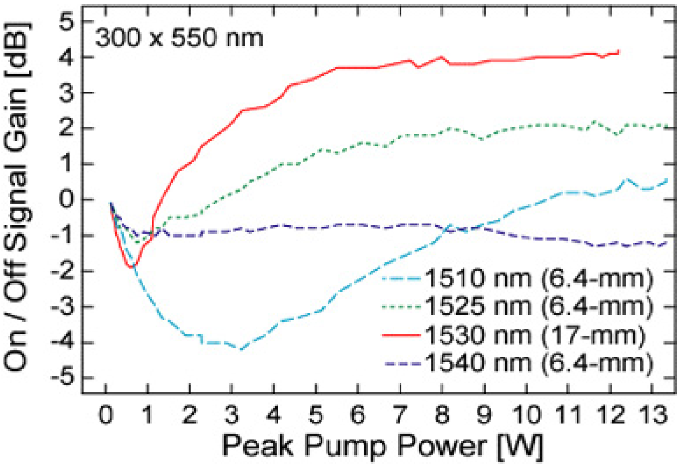

Figure 3. *Plots of the measured four-wave mixing gain versus pump power for various pump wavelengths in silicon waveguides of different lengths. The transverse dimension of all waveguides is 300×550nm.*

We performed experiments in these waveguides with anomalous dispersion and were able to observe amplification up to 5dB over a bandwidth of 30nm. Figure 3 shows a plot of the amplification of the signal field for various waveguide dimensions. Initially, at lower powers the signal field experiences loss due to the two-photon induced generation of free carriers by the pump wave. However, at higher powers, the FWM process becomes phase-matched, which results in a net amplification despite the presence of nonlinear losses.

The strong light enhancement in photonic structures coupled to the large non-linearities in bulk silicon offer the promise that FWM amplification can be achieved using ultra-low pump powers, of the order of tens of milliWatts. To further enhance the efficiency of the process, one could integrate junctions that sweep out the free carriers generated by the pump beam and lead to losses.

Using enhanced FWM in silicon waveguides can enable architectures in which light is amplified in regions of the chip

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where losses are high. In addition, the wavelength conversion and the high bandwidth of the FWM process can allow on-chip wavelength-division-multiplexing architectures with unprecedented bandwidth and low power.

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