Continuum generation and carving on a silicon chip

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Self-phase modulation is utilized to generate a continuum of wavelengths on a silicon chip. The propagation of near transform-limited, picosecond pulses (3 ps) through a micron sized silicon waveguide results in the generation of a spectral continuum. This spectral continuum is then carved by microdisk resonators that are integrated three dimensionally on the same chip, resulting in multiple wavelength channels, with the farthest channel being around 3.1 nm away from the center wavelength of the seed pulse. This technique can potentially enable wavelength division multiplexing at the chip level using a single off-chip laser. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2766962]

On-chip optical interconnects are being developed to address the limitations of metal interconnects such as latency, power dissipation and lack of adequate bandwidth, problems that are exacerbated by the scaling of transistor size.[1–3] For photonics to offer overall performance advantages over copper interconnects, it is necessary to use wavelength division multiplexing (WDM) technique that enables the transmission of multiple signals on the same optical interconnect.[4,5] Here we report a potential solution to this problem. Utilizing self-phase modulation, a continuum of wavelengths is generated on chip by propagating optical pulses from an off-chip laser in a silicon waveguide.[6,7] This continuum is then carved by microdisk optical filters that are integrated three dimensionally (3D) on the same chip. This approach to on-chip WDM addresses one of the key challenges that optical interconnects will face. Increasing power dissipation on microprocessors, caused by the rapid increase in the number of transistors on a chip and the clock frequencies, is the central problem in the semiconductor industry.[8] Integration of photonics on a chip should be performed in such a way that photonics does not severely increase the power dissipation of the chip. Among various photonic devices, laser diodes and their driver circuitry are the most power-hungry devices. Keeping the laser off chip is attractive because it does not exacerbate the heating problem. However, coupling several lasers onto a chip is also not desirable due to complexity in packaging. A WDM interconnect architecture that only requires a single off-chip laser does not exacerbate the chip heating problem yet offers simplicity in packaging. Another attribute lies in the fact that a continuum generated via self-phase modulation (SPM) is coherent across the spectrum, resulting in phase-synchronous wavelength channels.[9,10] This opens up avenues for on-chip coherent optical communications with potential for improvement in sensitivity, signal-to-noise ratios (SNRs), as well as increased spectral efficiency for, and the ability to realize optical code division multiple access.[11]

The intensity dependent refractive index of a nonlinear medium modulates the phase of the optical wave as it propagates through it, a phenomenon known as SPM. When the optical wave is in the form of intense, short pulses, this self-phase modulation leads to the generation of additional wavelengths known as the spectral continuum.[9,12] In silicon, the intensity-dependent refractive index that leads to SPM and the generation of spectral continuum has two contributions: (i) the Kerr nonlinearity and (ii) free-carrier refraction, the modulation of the refractive index of the medium through free carriers (electrons and holes) that are generated by two photon absorption (TPA).[6,7] Continuum generation and carving is illustrated in Fig. 1, where an intense optical pulse creates a range of wavelengths as it traverses a silicon waveguide. Broadening of the optical spectrum induced by SPM and its dependence on pulse parameters, carrier lifetime, and waveguide propagation loss have been studied both experimentally and theoretically.[6,7,13]

Continuum generation in silicon is more complicated than that in fiber because of free-carrier dynamics. The Kerr effect produces blueshifted spectral components on the trailing edge and redshifted spectral components on the leading edge of the optical pulse envelope. On the other hand, free-carrier refraction causes blueshift on both edges. Thus, at the leading edge of the pulse, Kerr and free-carrier effects tend to counteract each other, whereas they add at the trailing edge to produce a net blueshift for the broadened spectrum. Free carriers also cause the absorption of optical energy within the pulse. More carriers are generated toward the trailing edge, as the free-carrier density follows the time integral of the pulse shape. Thus, the blueshifted frequency components that reside in the trailing edge suffer more attenuation as compared to the redshifted components. Furthermore, TPA also reduces the peak power of the optical pulse further limiting the amount of spectral broadening. Raman scattering is another prominent nonlinear interaction in silicon waveguides. This effect is negligible in the experimental conditions employed here because of the short pulse widths and the ensuing spectral broadening prevent appreciable Raman scattering from occurring.[6]

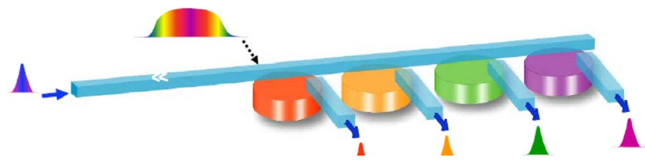

FIG. 1. (Color online) Schematic of continuum generation and carving on a silicon chip.

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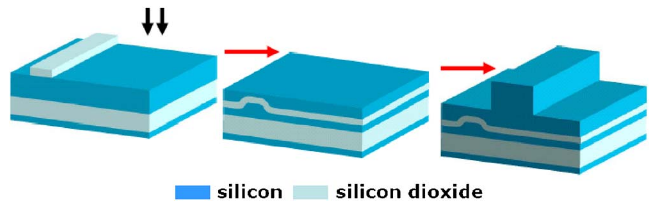

FIG. 2. (Color online) Schematic of the fabrication of three-dimensionally integrated structures using the process of SIMOX 3D sculpting.

Continuum generation and spectral carving have been demonstrated utilizing glass fibers and bulk optical filters, with the goal of creating multiwavelength sources for optical networking.[14] The tight optical confinement and the resulting enhancement of nonlinearities in silicon waveguides make it possible to achieve continuum generation on the length scale of a chip. The small optical mode allows us to couple the continuum to microcavity based filters that have a very small footprint. All these attributes lend themselves to an on-chip continuum source.

We use a fabrication technique known as separation by implantation of oxygen (SIMOX) 3D sculpting (Fig. 2) developed by us and previously used to demonstrate vertically coupled microdisk resonators and monolithic optoelectronic integration in silicon.[15,16] This approach leads to efficient use of wafer real estate, a central requirement in microelectronic manufacturing.[17] Briefly, the process of SIMOX 3D sculpting involves the implantation of oxygen ions into a silicon-on-insulator substrate, patterned with thermal oxide, to create buried waveguide structures.[15] A high temperature anneal after the implantation aids the formation of a continuous layer of silicon dioxide, that separates the subsurface waveguide structures from a surface silicon layer. In this work, subterranean microdisk resonators are realized in this fashion, and the surface silicon layer is used as the seed layer to grow silicon epitaxially on the substrate. After the epitaxial growth, waveguides are etched on the surface silicon layer.

The optical micrograph of the top view of the device employed to generate and carve the spectral continuum is shown in Fig. 3(a). It consists of a 2 cm long silicon waveguide on the surface silicon layer followed by three microdisk resonators of radii 39.5, 40, and 40.5 μm in the buried silicon layer. Disks of different radii were used to obtain resonators with slightly shifted resonance wavelengths. These microdisks are coupled through an intervening layer of silicon dioxide to the straight waveguide that generates the continuum as well as the curved waveguide sections that drop part of the continuum carved by the resonators. A schematic section of the device that illuminates the 3D nature of the device is shown in Fig. 3(b). The intervening layer of oxide through which the coupling of light takes place is omitted in Fig. 3(b) for the simplicity of illustration. Figure 3(c) shows the cross sectional schematic of the device indicating the vertical dimensions of different layers and the width of the surface waveguide.

The devices were tested by propagating near transform limited optical pulses of width 3 ps and peak power of 270 W, generated from a passively mode-locked laser, of repetition rate 20 MHz, operating around 1550 nm. Considering the reflection losses and mode mismatch losses, we estimate that the peak power of the pulses inside the waveguide at its input was around 85 W. A comparison of the optical spectrum at the input of a purely straight waveguide,

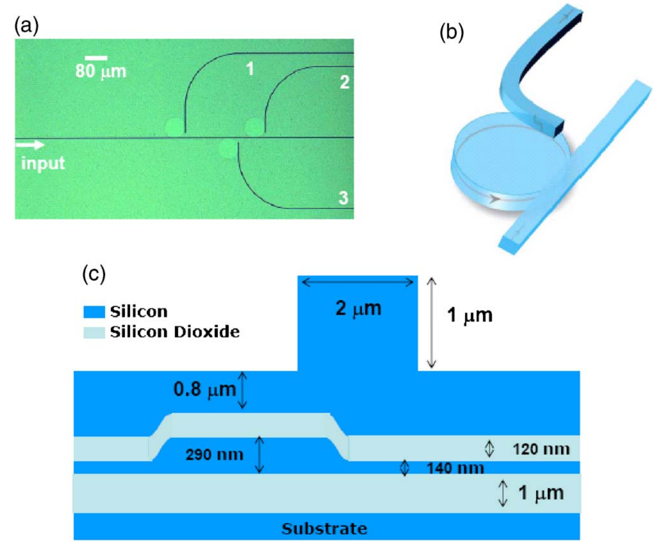

FIG. 3. (Color online) (a) Optical micrograph of the topview of the continuum carving device. (b) Magnified schematic of the coupling of the straight waveguide on the surface silicon layer to the microdisk resonator in the subsurface layer. (c) A cross sectional schematic of the device indicating the vertical dimensions of different layers and the width of the surface waveguide.

of 2 cm length, to the broadened continuum at its output is shown in Fig. 4. At the −20 dB level, the output spectrum shows a 2.5-fold increase in its width over the input. This value is comparable to the threefold increase predicted by the simulations. The capability of SPM induced spectral broadening in redistributing the energy in the input pulse to a broader spectral bandwidth is clearly demonstrated in this figure. On the shorter wavelength side, the input spectrum reaches the noise floor at around 1548.3 nm, whereas the broadened spectrum reaches the noise floor only at 1542.3 nm. Noise floors are at 1552.6 and 1556.6 nm, respectively, for the input and the broadened spectra on the longer wavelength side.

Figure 5 depicts the normalized spectral response of a device where the straight waveguides are followed by the set of buried resonators that carve the continuum. It may be seen that three wavelength channels at 1547.9, 1548.5, and 1549.1 nm have been created by carving the continuum, with the farthest channel being around 3.1 nm away from the center wavelength of the seed pulse. As discussed previously,

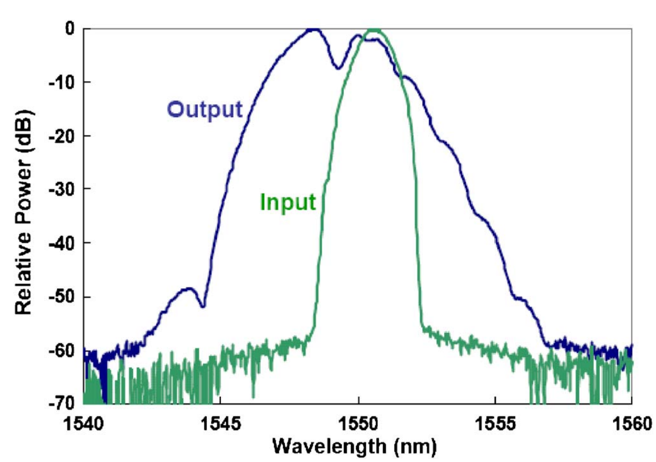

FIG. 4. (Color online) Spectral characteristics of the continuum generated in a silicon waveguide, along with the input spectrum.

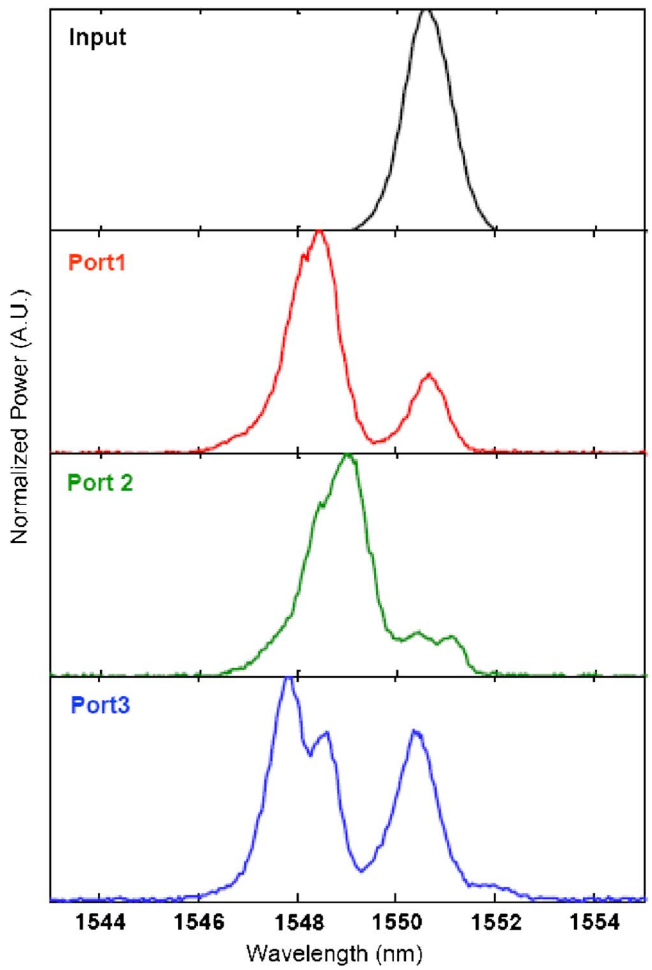

FIG. 5. (Color online) Wavelength channels generated by carving the continuum using microdisk resonators.

the input spectrum reaches the noise floor at around 1548.3 nm on the shorter wavelength side. Thus, the creation of channels in the wavelength region where the input spectrum has negligible amount of energy illustrates the suitability of method of continuum carving for on-chip WDM applications. The secondary peaks observed in the carved spectrum correspond to the free spectral range of the microdisk resonators which is around 2.6 nm. The minor peak observed at 1548.3 nm for the spectrum at port 3 could be due to the excitation of higher order modes in the disk resonator.

Although the 2 cm long waveguides are used here, this length may be reduced using waveguides with smaller modal area. In such waveguides, the optical intensity and hence SPM is enhanced leading to more rapid continuum generation. Our simulations indicate that, using a waveguide with a modal area of 0.75 μm^2 offers fivefold spectral broadening in only 4 mm of waveguide length, given input pulses of peak power 200 W. Using a serpentine geometry with bend radii of about 2 μm,[18] such a waveguide can be realized in a 100×200 μm^2, area. Another approach to continuum generation is based on soliton fission which occurs in waveguides with zero or anomalous group velocity dispersion.[13] Simulations show threefold spectral broadening of 50 fs pulses in a 3 mm long silicon waveguide of modal area 0.32 μm^2. This dispersion engineering is achieved in waveguides with submicron lateral dimensions where the waveguide dispersion is equal or larger than the material dispersion. While this approach requires precise control over waveguide dimensions, it produces flat spectral regions and has a low peak power requirement. It is also more likely to lead to coherence degradation and instability in the pulse train.[10,19,20] Continuum generation in the normal dispersion regime, employed here, avoids this effect.

In summary, a possible method to generate multiple wavelength sources on a chip using a single off-chip laser is demonstrated in this work. Spectral continuum generated by the propagation of an intense optical pulse through a silicon waveguide is carved using 3D integrated microresonators to generate discrete wavelength channels on a chip.

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