## Summary

We have reported the fabrication and characterization of holographically written integrated Bragg gratings and DBR cavities in $Al_2O_3$ ridge waveguides. Due to the low total waveguide propagation losses of 0.14 ± 0.07 dB/cm and grating induced losses of 0.08 ± 0.01 dB/cm, it was possible to realize Bragg gratings with reflectivities exceeding 99%. This enabled the demonstration of passive DBR cavities with a finesse of more than 147 and a Q-factor as high as $1.02 \pm 0.01 \times 10^6$. This is, to our knowledge, the highest demonstrated Q-factor of any passive monolithic DBR cavity on a silicon chip. The ability to integrate Bragg grating structures with optical waveguides also provided the opportunity to demonstrate an efficient, low threshold, monolithic $Al_2O_3:Yb^{3+}$ DBR waveguide laser operating at 1021.2 nm. The laser exhibited a pump-power-limited output power of 47 mW and a slope efficiency of 67%.

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# Nonlinear optics on silicon: towards integrated long-wavelength light sources

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*The short-wave and mid-infrared wavelength region, often referred to as the molecular fingerprint region, has an enormous potential for spectroscopic applications. Silicon's transparency from 1.1 um up to 7 um could potentially be used to make a platform for a whole new class of compact devices for gas trace sensing, environmental monitoring etc. By using the large effective* $\chi^{(3)}$ *nonlinearity, light generation by nonlinear mixing in this new wavelength region is demonstrated. We present both a silicon broadband supercontinuum spanning from the telecom window into the mid-infrared as well as a silicon-based widely tuneable optical parametric oscillator.*

## Introduction

Many molecules have distinct absorption features in the short-wave and mid-infrared wavelength range. These absorption features resulting from the molecular vibrational states of the molecules are specific and act as a fingerprint for these molecules. For now, silicon has been used primarily to construct planar lightwave circuits in the telecom wavelength range. However due to its transparency up to 7 um, silicon waveguides can be used as a platform to guide this mid-infrared light. This would enable to integrate complex functions on a compact silicon chip and enable a whole new set of applications for spectroscopic sensing. However, to probe these absorption features tuneable sources or broadband sources need be integrated on these chips. The integration of such sources with a silicon chip is not straightforward. However, the high intrinsic nonlinear $\chi^{(3)}$ nonlinearity can be used to generate new wavelengths. Indeed by combining the high intensities obtained by the high confinement in silicon wire waveguides with the enormous nonlinearity of the material, low-threshold nonlinear effects can be obtained. The nonlinear interactions can be further enhanced by using dispersion engineered wire waveguides. In these dispersion engineered waveguides phase matching between the optical waves in the nonlinear optical process is satisfied. Here we demonstrate the use of nonlinear optics in silicon waveguides to generate a broadband supercontinuum light source as well as a widely tunable silicon based optical parametric oscillator.

## Nonlinear optics in silicon nanowire waveguides in the mid-infrared

At telecommunication wavelengths silicon suffers from two-photon absorption, which limits the efficiency of nonlinear processes in silicon wire waveguides. Given the 1.12 eV bandgap of silicon, this two-photon absorption process disappears at wavelengths

beyond 2.2 μm. In this work, 900 nm wide and 220 nm thick silicon strip nanowire waveguides with an air top cladding are pumped close to 2.2 um to achieve efficient nonlinear interactions. The waveguide cross-section is shown in the inset of Figure 1. Using a cut back technique, the TE mode waveguide propagation loss is found to be approximately 2.5 dB/cm across the 2050-2450 nm wavelength range. In Figure 1 the higher order dispersion terms of the waveguide are shown. These waveguides are designed to have a negative second order dispersion and positive fourth order dispersion to achieve phase matching in the four wave mixing process.
Indeed, efficient phase matching in the four wave mixing occurs when [4]

$$\Delta k = \Delta k_{lin} + \Delta k_{nonlin} = 2k_{pump} - k_s - k_i - 2\gamma P = 0 \qquad (1)$$

in which $k_{pump}$, $k_s$ and $k_i$ are the linear propagation constants of the pump, signal and idler wave respectively. The term $2\gamma P$, in which $\gamma$ is the effective nonlinear parameter of the waveguide and $P$ is the peak power of the pump pulse, accounts for the self-phase and cross-phase modulation of the interacting waves. Using a Taylor expansion of the waveguide dispersion relation around $\omega_{pump}$ and taking into account the conservation of energy in the four wave mixing process, this results in a phase matching condition

$$-\beta_2 \Delta\omega^2 - \frac{1}{12}\beta_4 \Delta\omega^4 - 2\gamma P = 0 \qquad (2)$$

in which $\Delta\omega$ is the frequency detuning between pump and signal (and also between pump and idler), $\beta_2$ the second order and $\beta_4$ the fourth order dispersion. By averaging the nonlinear susceptibility of bulk Si over the electric field of the fundamental TE polarized waveguide mode, the real part of the nonlinearity parameter is estimated to be $\gamma = 150\ (W \cdot m)^{-1}$ in the silicon nanowire being used.

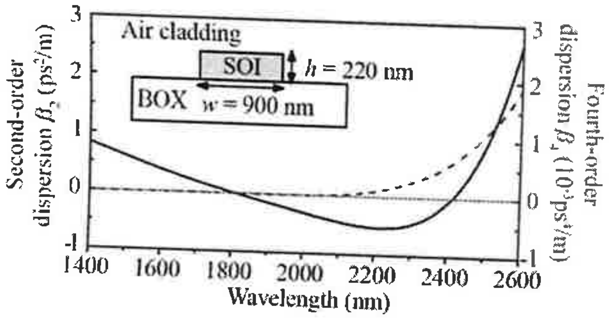


Fig. 1: Dispersion of the silicon photonic wire, simulated using a commercial finite element solver (RSoft FemSIM). The inset shows a cross section of the silicon wire waveguide.

## Supercontinuum generation

The supercontinuum generation experiments are conducted using a picosecond pulse train at a center wavelength of 2120 nm as the pump (Coherent Mira-OPO, FWHM = 2 ps, repetition rate = 76 MHz). Figure 2 illustrates the evolution of the waveguide output spectrum as the input coupled peak pump power is gradually increased from 3.1 W (green trace) to 12.7 W (black trace). These spectra reveal that a number of different nonlinear processes ultimately combine to produce the broadband supercontinuum. At an input power of 3.1 W, a series of sidebands are generated in the vicinity of the pump at 2120 nm. Closest to the pump, two broad sidebands (labeled as MI(1)) are generated near wavelengths of 1990 nm and 2250 nm. Further away from the pump, a pair of narrowband peaks (labeled as MI(2)) appear at wavelengths of 1870 nm and approximately 2510 nm. Both the broad and narrow sideband pairs originate from modulation instability, i.e. the amplification of background noise at wavelengths for which the phase matching condition in Eq. (2) is satisfied. At a pump power of 7.9 W, several new spectral components are observed, peaked near 1700 nm and 1600 nm respectively. The term at 1700 nm is generated through cascaded four wave mixing (FWM), where the original MI(2) peak at 1890 nm serves as the degenerate pump and the input pulse at 2120 nm acts as the signal. At maximum power the supercontinuum was inspected with an FTIR, this revealed that the supercontinuum [1] spans from 1.53 um up to 2.55 um.

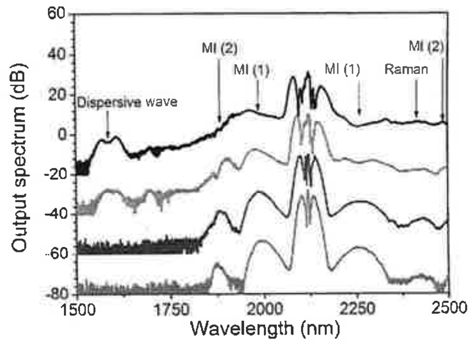


Fig. 2. Measured output spectrum for increasing values of coupled input peak power: 3.1 W (green), 4.3 W (blue), 7.9 W (red) and 12.7 W (black).

## Widely Tuneable Silicon Mid-Infrared Optical Parametric Oscillator

The broadband on-chip parametric gain demonstrated by the modulation instability sidebands [3] can be combined with optical feedback in order to achieve optical parametric oscillation over a broad wavelength range [4]. The synchronously pumped fiber optic loop configuration employed to construct the mid-IR OPO is illustrated in Figure 3. The mid-IR pumped photonic wire waveguide serves as the core gain element within the fiber loop. The cavity of the OPO is formed by a loop of standard single mode fiber, along with a variable free-space delay element, which facilitates temporal synchronization of the re-circulating amplified pulses with successive pump pulses. Due to the absence of special purpose wavelength multiplexers/demultiplexers within the mid-IR wavelength range of operation, a 90/10 coupler is used to combine the cavity pulses with successive pump pulses after each round-trip. Polarization controllers are used to align both the pump and cavity pulses to the quasi-TE-mode at the input of the photonic wire. The output of the silicon-fiber OPO is monitored by a mid-infrared optical spectrum analyzer (OSA). The high dispersion of the single mode fiber feedback loop at wavelengths beyond 2000 nm allows for wavelength selective feedback. By adjusting the round-trip time using the free-space variable delay line, a particular temporal "slice" of the circulating amplified pulse is selectively synchronized with the pump pulse train. The dispersion in the fiber loop likewise ensures that only one particular wavelength within the silicon parametric gain spectrum can be synchronized with the pump pulses, and thus enables broadband tuneability of the oscillator wavelength via delay tuning. The energy of the output pulses as a function of the output wavelength for pump pulses with an energy of 48 pJ at 2175 nm is shown in Figure 4. It was demonstrated that the OPO is tuneable over a 75 nm-wide band centered around the gain peak at 2075 nm.

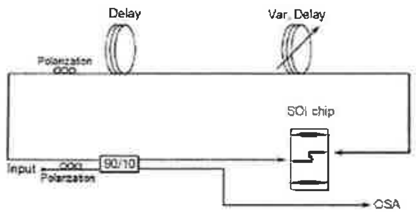


Fig 3. Configuration of the synchronously-pumped silicon-fiber OPO.

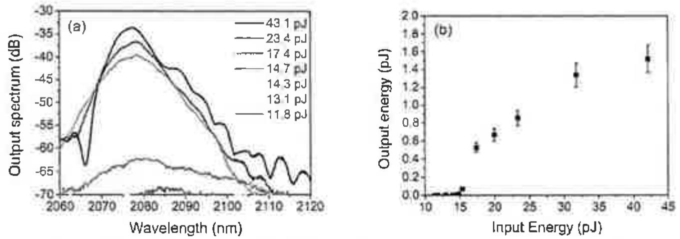


Fig 4 Output spectrum of the silicon-fiber OPO for different pump pulse energies, when the fiber cavity is tuned to an output wavelength of 2075 nm. (b) On-chip output pulse energy versus the coupled input pump pulse energy.

## Conclusion

Nonlinear optics has a huge potential for integrating tuneable or broadband sources in the mid-infrared on a silicon chip. A broadband supercontinuum spanning from the telecom wavelength range into the mid-infared was demonstrated as well as a tuneable silicon-based optical parametric oscillator.


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# Multi-wavelength Laser Based on Filtered-feedback


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*We present a novel multi-wavelength laser based on on-chip filtered optical feedback. The monolithically integrated device consists of four Fabry–Pérot (FP) lasers that are wavelength-locked by an on-chip filtered-feedback section. The FP mirrors are formed by two on-chip multimode interference reflectors (MIRs), and the feedback section contains four phase shifters and a reflective arrayed waveguide grating to provide the filtered-feedback. By controlling the current injection to the lasers, single mode operation in each channel can be achieved. In this paper the design, fabrication and the first measurement are presented.*


## I. Introduction

The progress in the wavelength-division-multiplexing (WDM) technologies for broadband optical communication systems has called for multi-wavelength light sources. A monolithically integrated multi-wavelength laser is particularly in demand due to its economy and efficiency in increasing the flexibility of the WDM system. Different integrated MWLs have been realized. For example, tunable distributed Bragg reflector (DBR) laser arrays [1], micro-disk laser arrays [2] or MWL made by integrating a semiconductor optical amplifier (SOA) array with a multiplexer in one cavity [3-5] in a linear or ring configuration.

Here we present a novel multi-wavelength laser based on on-chip filtered optical feedback. The filtered-feedback scheme has been demonstrated in a fast tunable laser device [6]. Here we implement it to realize a multi-wavelength laser. The monolithically integrated device consists of four Fabry–Pérot (FP) lasers that are wavelength-locked by an on-chip filtered-feedback section. The FP cavities are formed by two on-chip broadband multimode interference reflectors (MIRs) [7], and a feedback section containing phase shifters and a reflective arrayed waveguide grating (AWG) to provide the filtered-feedback. Because the AWG that is used for wavelength selection is outside the main laser cavity, in contrast to conventional AWG based MWLs [3-5], the gain from the laser cavity does not need to compensate the loss from the AWG, and the main cavity can be much shorter. This configuration makes the laser have a lower threshold current, a higher output power and allows for accurate wavelength selection. In this paper the design and fabrication (section II) and the first measurement of the integrated device (section III), are presented.

## II. Design and fabrication

The operating principle of the multi-wavelength laser can be understood from its schematic representation in Fig. 1a. This device consists of an array of FP lasers, each of which is formed by an SOA and two on-chip broadband reflectors that form the FP-cavity. The reflectors also provide some transmission to and from the laser cavity. One side of each FP laser is coupled to an AWG filter through a phase shifter. These FP lasers generate a broad spectrum of longitudinal modes, of which the spacing is determined by the cavity length. The AWG multiplexes the light of the FP laser channels to a common output, which is connected to another on-chip broadband reflector. This reflector will reflect the light and subsequently, the AWG will

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