Millimeter-Scale Chip-Based Supercontinuum Generation for Optical Coherence Tomography

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Abstract: We demonstrate a supercontinuum light source for OCT imaging in a compact 1 mm² Si₃N₄ chip. We achieve 105 dB sensitivity and a 6-dB sensitivity roll-off at 1.81 mm with only 300 µW incident power. © 2021 The Author(s)

Supercontinuum sources for optical coherence tomography (OCT) have raised great interest as they offer broad bandwidth and excellent spatial coherence [1-6]. However, commercial supercontinuum sources suffer from high excess noise and require very high power to achieve broad bandwidth and high sensitivity, which needs to be spectrally shaped and attenuated with conventional bulk optical filters.

Here we demonstrate a supercontinuum light source for OCT imaging in a compact 1 mm x 1 mm silicon nitride (Si₃N₄) chip. Due to high optical confinement and intrinsic nonlinearity in Si₃N₄, the waveguide has a nonlinearity parameter of 2710 W⁻¹km⁻¹, which is over 100 times that of highly nonlinear fibers commonly used in commercial supercontinuum systems, enabling power efficient supercontinuum generation [7,8] with no additional optical filtering needed to shape or attenuate the spectrum. This enables us to obtain better sensitivity and sensitivity roll-off range with a fraction of the power on the sample and the supercontinuum spectrum can be shaped with proper group-velocity-dispersion engineering in the Si₃N₄ waveguides by changing the waveguide width, which is easy to implement and thus provides more flexibility.

Fig. 1. (a) Top view optical microscope image of multiple 5 cm long high confinement waveguides fabricated on the same chip. The zoom-in shows that the fabricated waveguide only occupies an area of 1 mm². (b) Measured supercontinuum spectrum generated using the Si₃N₄ waveguide. The spectrum has a 30-dB bandwidth of 445 nm covering 990 nm to 1435 nm and a flat 3-dB bandwidth ranging from 1264 nm to 1369 nm with input pump pulse energy of only 25 pJ.

Using a 5-cm-long waveguide with a cross-section of 730 × 840 nm, we achieve a broadband and spectrally flat supercontinuum spectrum with 200-fs pump pulses centered at 1300 nm with pulse energies of 25 pJ, which corresponds to an average pump power of 2 mW. The fabricated waveguide only occupies an area of 1 mm² and the supercontinuum spectrum generated by the Si₃N₄ chip is directly measured with an optical spectrum analyzer as shown in Fig. 1. The 30-dB bandwidth spans 990 nm to 1435 nm. The 3-dB bandwidth ranges from 1264 nm to 1369 nm (105 nm), corresponding to an axial resolution of 7.28 µm in air (4.86 µm in tissue).

We integrate our Si₃N₄ chip into a fiber-coupled spectral domain (SD) OCT system centered at 1300 nm to measure the performance of the Si₃N₄-OCT system. We demonstrate 105 dB sensitivity and a 6-dB sensitivity roll-
off at 1.81 mm with only 300 µW power on the sample at an A-line rate of 28 kHz. For comparison, commercial supercontinuum systems show 95 dB and a 6-dB sensitivity roll-off at 1.25 mm with 4 mW of power on the sample at an A-line rate of 40 kHz (SuperK Extreme) [9] and 81 dB sensitivity and a 6-dB sensitivity roll-off at 1.20 mm with 4 mW power on the sample at an A-line rate of 25 kHz (SuperK Compact) [10], respectively. We measure the 6-dB sensitivity roll-off range to be 1.81 mm in our system, compared with the 6-dB sensitivity roll-off range of 1.25 mm using a state-of-art SuperK Extreme system that needs 10x more power on the sample. Our measured sensitivity is close to the theoretical shot noise limited prediction assuming a spectrometer detection efficiency of 0.4. The axial resolution is measured to be 7.45 µm in air (4.97 µm in tissue), which is in good agreement with the theoretical axial resolution of 7.41 µm (in air), accounting for the wavelength detection range of the spectrometer.

We demonstrate the ability of our Si3N4 chip OCT system to resolve diverse microscopic biological tissue architecture by imaging human breast tissue. The human breast tissue samples were collected from patients undergoing mastectomy procedures at Columbia University Irving Medical Center. The specimens were fixed in formalin and imaged ex vivo within 24 hours of surgical excision. Imaging was performed at an A-line rate of 28 kHz. The total acquisition time of a single image (OCT B-scan) is 35 ms and the imaging depth is 2.52 mm. Figure 2 shows a volumetric 3D scan of healthy breast tissue, which demonstrates important microscopic structural features of healthy breast tissue such as milk ducts, lobules, adipose (fat), and stroma (connective tissue). We did not average or pre-process these images. We process the OCT images from the raw data by performing background subtraction, linear-k interpolation, apodization, and digital dispersion compensation.

In conclusion, we demonstrate a supercontinuum light source for OCT imaging in a compact 1 mm2 Si3N4 chip that can be directly pumped at 1300 nm and does not require any optical filtering to shape or attenuate the spectrum. Our Si3N4 chip platform achieves 105 dB sensitivity and 1.81 mm 6-dB sensitivity roll-off with only 300 µW power on the sample. Our experiment demonstrates the principle of generating supercontinuum using an integrated Si3N4 photonics platform targeted for OCT imaging and paves the way for utilizing integrated photonics platforms in the field of biomedical optics in the future.

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