Millimeter-scale chip-based supercontinuum generation

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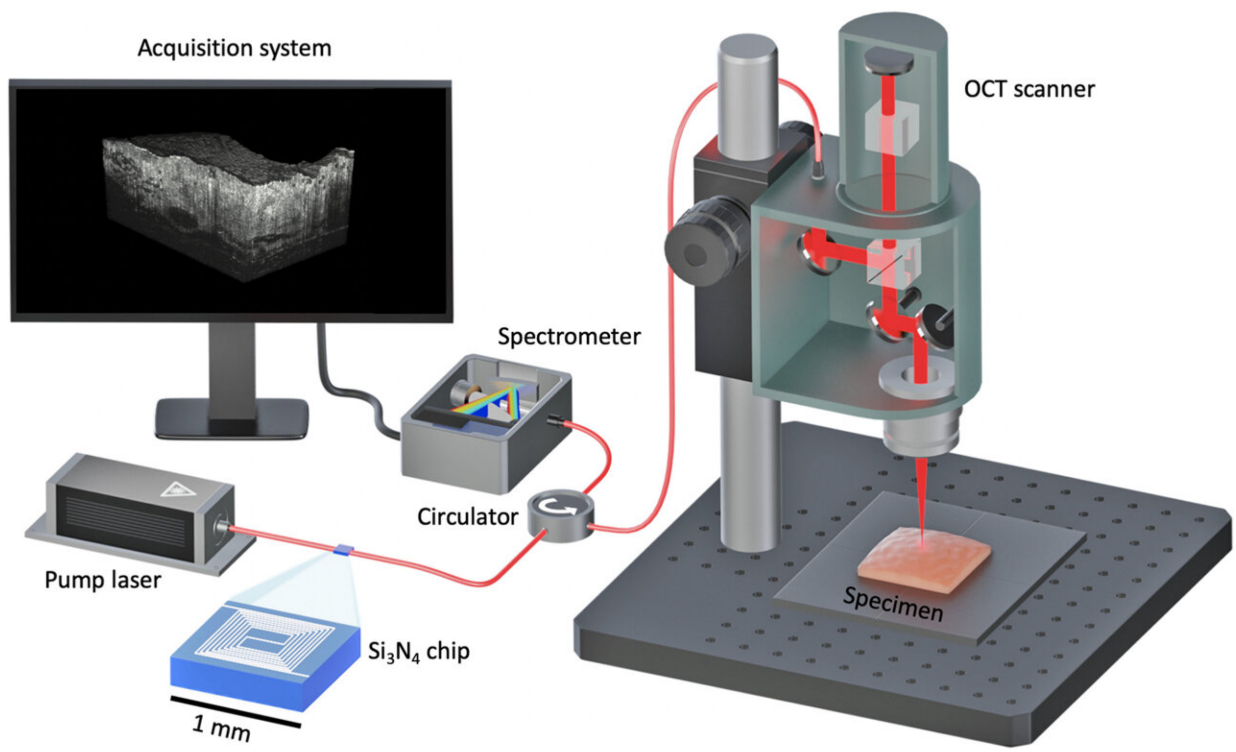


Schematic of a fiber-coupled SD OCT system with a supercontinuum source generated by the Si3N4 waveguide. Science Advances, doi:10.1126/sciadv.abg8869

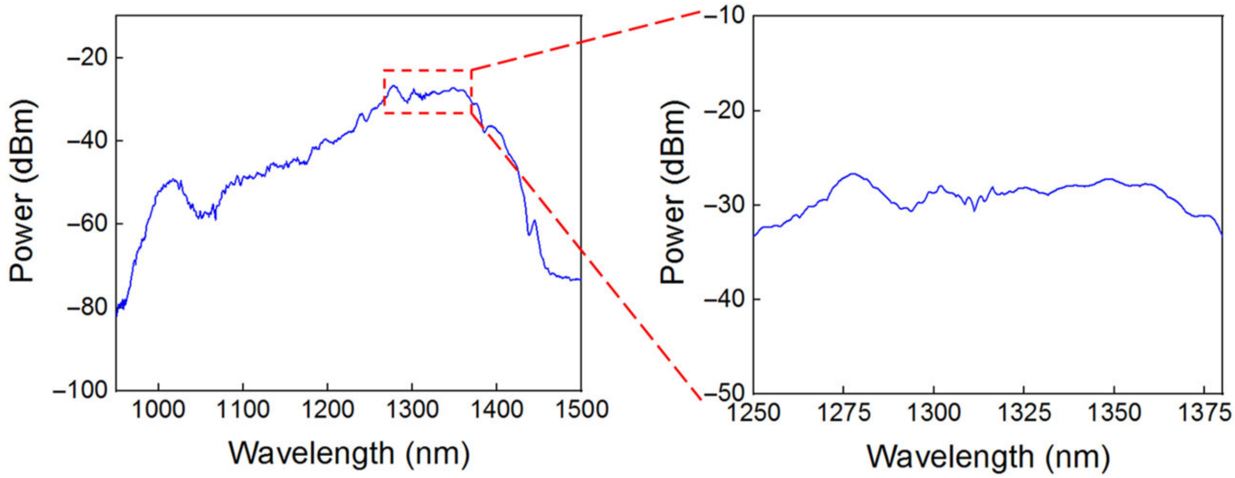
In optics, when a collection of nonlinear processes act together on a pump beam, the resulting spectral broadening of the original pump beam gives rise to a supercontinuum. Supercontinuum sources for optical coherence tomography are of great interest since they provide a broad bandwidth for high resolution and high-power imaging sensitivity. For commercial fiber-based supercontinuum systems, researchers use high pump powers to generate a broad bandwidth and customized optical filters to modulate the spectra. In a new report now published on *Science Advances*, Xingchen Ji and a research team in electrical engineering, biomedical engineering and applied physics at the Columbia University, New York, U.S., introduced a supercontinuum platform based on a 1 mm^2 silicon nitride photonic chip for optical coherence tomography (OCT). The researchers directly pumped and efficiently generated a supercontinuum near 1300 nm and used the setup to image biological tissues and show the strong imaging performance of the device. The new chip will facilitate portable OCTs and integrated photonics during optical imaging studies.

Medical Imaging Systems

Optical coherence tomography (OCT) is a label-free, three-dimensional optical imaging modality of high resolution. The OCT imaging platform is a standard of care in medicine, including ophthalmology, dermatology, gastroenterology and breast cancer imaging. While supercontinuum light sources for OCT offer a broad bandwidth, they require a very high source of power to accomplish a broad bandwidth and strong performance relative to the required sensitivity range. Commercial supercontinuum sources are also bulky in size and have demonstrated low efficiency of supercontinuum generation. To overcome these limits, Ji et al. developed a supercontinuum light source for OCT imaging in a compact silicon nitride (Si_3N_4) photonic chip. Silicon nitride has a high refractive index, a high nonlinear parameter, a wide transparency window and compatibility with large-scale semiconductor manufacturing . As a result of high optical confinement and intrinsic nonlinearity in silicon nitride, the waveguide showed a nonlinearity parameter approximately 100 times larger than that of highly nonlinear fibers used in commercial supercontinuum systems. The waveguides developed in the work occupied an area of 1 mm^2. On account of the output spectral characteristics for imaging, the team did not require additional optical filtering to shape the spectrum.

The silicon nitride chip integrated optical system

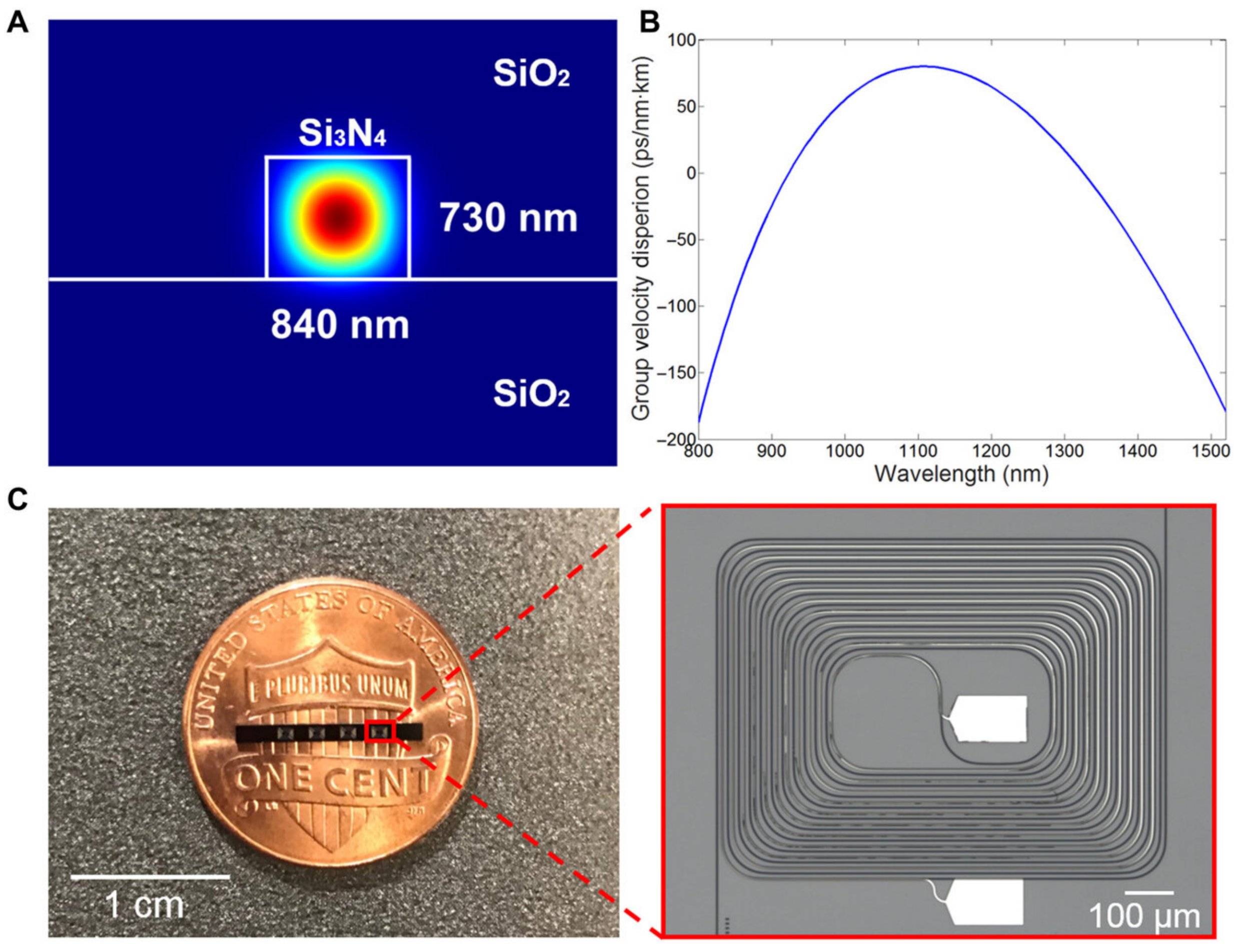
The research team integrated the silicon nitride chip into a fiber-coupled spectral domain-OCT system centered at 1300 nm. Ji et al. sent the output light from the silicon nitride chip directly to the OCT interferometer through a circulator and measured the performance of the silicon nitride-OCT system to record a sensitivity of 105 dB at 300 µW power. Comparatively, a commercial supercontinuum showed 95 dB with 4 mW power. The sensitivity measured in the setup was close to the theoretical shot noise limited prediction. Using the silicon nitride chip-OCT system, Ji et al. resolved diverse microscopic biological tissues of healthy human breast tissue. To accomplish this, the team received tissue samples from patients undergoing mastectomy procedures at Columbia University Irving Medical Center. They fixed the specimen in formalin and imaged them ex vivo, 24 hours after surgical excision. The resulting volumetric three-dimensional (3D) scan of healthy breast tissue demonstrated important microscopic structural features, including milk ducts, lobules, fat and connective tissue. The researchers processed the OCT images from the raw data by performing background subtraction and digital dispersion compensation.



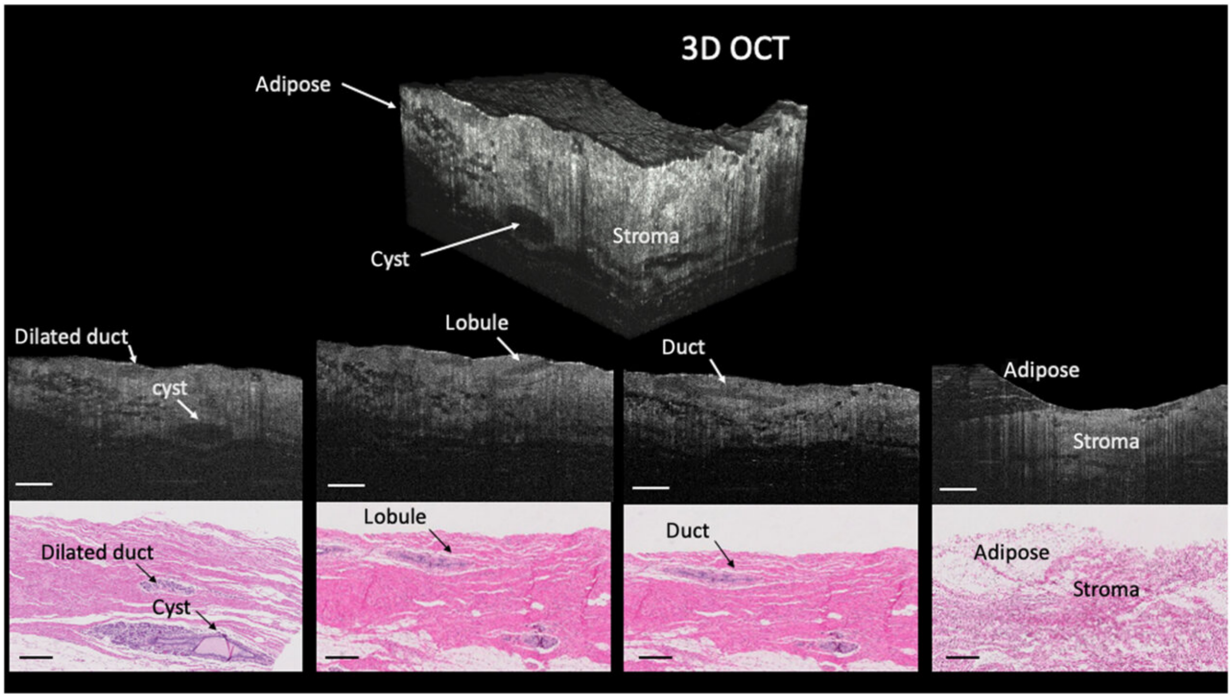
Measured supercontinuum spectrum generated using the Si3N4 waveguide. The spectrum has a 30-dB bandwidth of 445 nm covering 990 to 1435 nm and a flat 3-dB bandwidth spanning 1264 to 1369 nm with an input pump pulse energy of 25 pJ. Science Advances, doi:10.1126/sciadv.abg8869

Materials for supercontinuum generation

Scientists can generate supercontinuum spectra using integrated waveguides of different material platforms. Silicon nitride has the benefit of being complementary metal-oxide-semiconductor- process-compatible, for large-scale manufacture at low cost. The material combined the benefits of ultralow loss, a high-index contrast between the waveguide and cladding index, alongside a wide transparency window to cover the wavelength windows of OCT imaging for various applications. All these characteristics made silicon nitride a good candidate for OCT imaging applications. Ji et al. also experimentally showed how the integrated silicon nitride photonics device formed a promising platform for OCT imaging and anticipate the development of integrated additional photonic platforms for biomedical imaging.



Simulations and microscope image of fabricated devices. (A) Mode simulation of a 730-nm-tall and 840-nm-wide waveguide showing that the fundamental transverse electric (TE) mode is highly confined in the geometry we have chosen. (B) Simulated group velocity dispersion (GVD) of our waveguide that provides close to zero GVD near 1300 nm, which allows us to directly pump and efficiently generate broadband supercontinuum at this wavelength without any postfiltering. (C) 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 × 1 mm2. Photo credit: Xingchen Ji, Columbia University. Science Advances, doi:10.1126/sciadv.abg8869



Volumetric 3D scan of healthy breast parenchyma acquired with a Si3N4 chip light source. Below, representative OCT B-scans from the 3D volume with corresponding hematoxylin and eosin histology. Visualized parenchyma structures included ducts, cysts, lobules, adipose, and stroma. Scale bars, 500 µm. Science Advances, doi:10.1126/sciadv.abg8869

Outlook

In this way, Xingchen Ji and colleagues developed a supercontinuum light source for optical coherence tomography (OCT) imaging in a compact silicon nitride photonic chip directly pumped at 1300 nm, without any optical filtering to shape the spectrum. The platform achieved a high sensitivity at low optical power on the sample. In contrast, with a state-of-the-art commercial supercontinuum source, researchers typically require 100 times more optical power to achieve comparatively similar sensitivity. The central wavelength of 1300 nm used in this study is well suited for imaging applications of tissue samples that required deeper penetration depths including human breast tissue, cardiovascular tissue and in dermatology research. The team adjusted dispersion engineering with integrated photonics to generate other spectral ranges at the scales of 1 µm or 800 nm. They functionalized the miniature supercontinuum light source developed in this work with an off-chip femtosecond pump laser, while efforts are also underway to miniaturize mode-locked lasers. The combined efforts of miniaturizing and packaging diverse building blocks of OCT using silicon photonics alongside the development of imaging probes can facilitate the realization of a high-performance, low-cost and fully miniaturized OCT system.

More information: Xingchen Ji et al, Millimeter-scale chip–based supercontinuum generation for optical coherence tomography, *Science Advances* (2021). DOI: 10.1126/sciadv.abg8869

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