On-chip Spectrometer for Low-Cost Optical Coherence Tomography

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ABSTRACT

Tornado Spectral Systems has developed a new spectrometer called OCTANE, the Optical Coherence Tomography Advanced Nanophotonic Engine, consisting of chip-based spectrometers for spectral domain optical coherence tomography (SD-OCT) systems. These devices include planar lightwave circuits with integrated waveguides fabricated on a planar silicon substrate. Our commercial prototypes include a NIR system centered at 860 nm, a bandpass of 70 nm, and 2048 output channels that can record TE and TM polarizations independently at an 80 kHz line scan rate. Intended to support low-cost, high-volume applications, these spectrometers are well-suited to SD-OCT for both biological and industrial non-destructive testing applications.

Keywords: spectrometer, planar lightwave circuit, waveguide, optical coherence tomography

1 INTRODUCTION

Spectral domain optical coherence tomography (SD-OCT) has become an important modality for acquiring non-destructive cross-sectional and volumetric images [1] in both biomedical applications (such as ophthalmology) and industrial applications. Unlike other forms of OCT, SD-OCT produces a full depth scan all at once by using a broadband light source, thus avoiding the cost and other limitations of using a tunable laser. However, central to this technology is a high-resolution spectrometer which often can be bulky, expensive, and sensitive to environmental conditions. Expansion of OCT into new markets, such as non-destructive testing (NDT) or point-of-care medical imaging, will require systems that scale better to these operating environments and market volumes. In short, there is a need for an alternative that is functionally similar to existing systems but robust, small, and low cost.

The Optical Coherence Tomography Advanced Nanophotonic Engine, or OCTANE, is a compact chip-based spectrometer platform designed specifically for demanding OCT applications. The OCTANE-860 is the first commercial prototype introduced by Tornado, with a 2.2 x 3.6 cm planar lightwave circuit (PLC) chip containing no moving parts. In this paper we will introduce the advantages of the OCTANE nanophotonics approach which match very well to the needs of next-generation OCT.

2 NANOPHOTONIC PLC

The core building blocks of the OCTANE-860 PLC (Fig. 1) are planar optical waveguides made from a silicon nitride core surrounded by silicon dioxide glass. Silicon nitride is a common dielectric material used in CMOS processing and is transparent in the NIR wavelength regions that are commonly used in OCT. Silicon nitride has a high refractive index (~2.0) compared to the glass cladding which allows high optical confinement leading to compact devices and micron-scale waveguide bending radii. Planar integrated optics allows the design of complex optical systems that can be orders of magnitude smaller than a free-space counterpart [2]. Additionally PLCs can be fabricated with the same techniques used in semiconductor foundries, facilitating low per-unit costs similar to the economies of scale for integrated circuits.

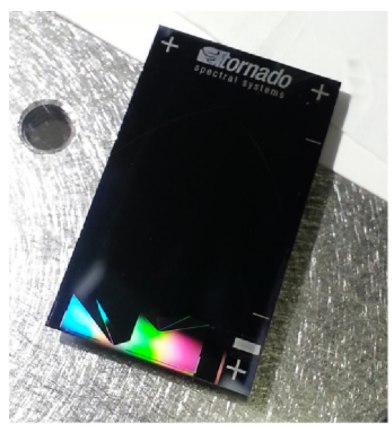
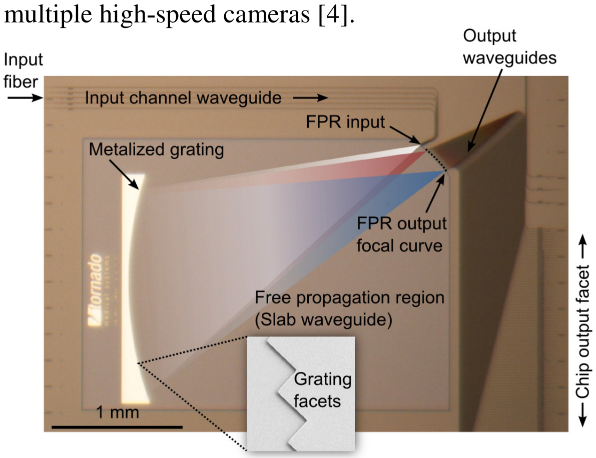
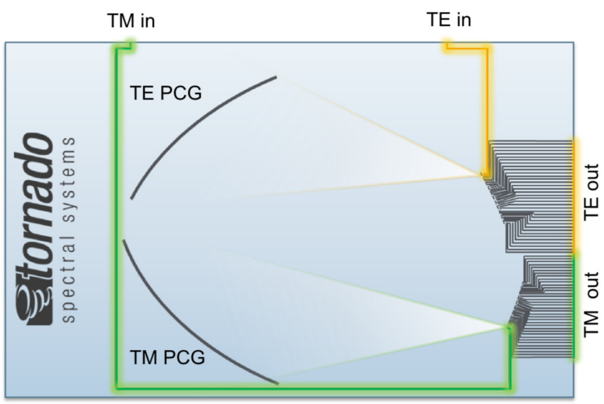


Figure 1: OCTANE-860 PLC (2.2×3.6 cm) containing planar concave grating (PCG) dispersive element.

The high refractive index and rectangular cross-section of a silicon nitride waveguide lead to strong birefringence which makes the waveguides naturally polarization-maintaining. The OCTANE-860 system architecture takes advantage of this property and includes two planar concave gratings (PCGs) [3], each optimized for a different input polarization, as shown in Figure 2(b). The outputs of each PCG are then routed adjacent to each other so that a single detector array can be used to measure the dispersed spectra, thereby reducing system costs and packaging complexity compared to a free space system which would require multiple high-speed cameras [4].



(a)



(b)

Figure 2: (a) Microscope image of a prototype PCG with 100 outputs. (b) Schematic of OCTANE-860 dual-polarization chip, including two PCGs with 1024 outputs each.

An early 100-channel prototype of a PCG is shown in Figure 2(a) to demonstrate the device operation. This device is called a planar grating because light is always confined within the plane of the chip by optical waveguides. Two types of optical waveguides are used in the system. First, a channel waveguide is coupled to an optical fiber at the input edge of the chip. The core of the channel waveguide has a rectangular cross-section that confines light in both transverse directions, resulting in an optical mode similar to that of the input fiber. The channel waveguide routes the optical signal to the input of the PCG, where it transitions to a slab waveguide that allows the mode to spread out laterally as it propagates. This slab waveguide is also called the free propagation region (FPR). The light then reflects off the grating, which is composed of micron-sized facets coated with reflective metal. The position and orientation of the facets are precisely designed to give the desired dispersion with minimum aberration. At the same time, the curvature of the grating focuses the light back towards the output of the FPR, where different wavelengths are dispersed to different positions along the output focal curve. Output channel waveguides are then tightly packed along the FPR output such that each waveguide captures a narrowband slice of the dispersed spectrum. The bundle of waveguides is then routed to the output facet of the chip which is butt-coupled to an array of detector pixels in the final package. The intensity from each waveguide is measured by a detector pixel, and the wavelength of each output is known after calibrating the system with a reference source.

Figure 3 shows the narrowband spectra coming from adjacent waveguides at the output of the chip before packaging to a detector, as measured with a fiber-coupled optical spectrum analyzer. Each curve shows the bandpass absorbed by one detector pixel in the packaged system. By design, the output samples are equally spaced in wavenumber which is advantageous for OCT data processing [5].

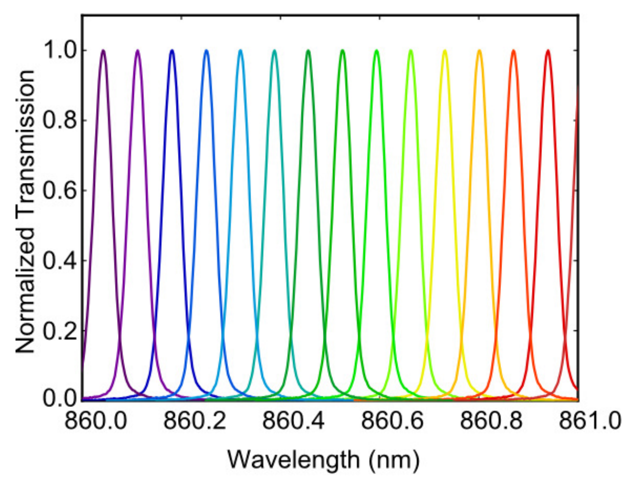


Figure 3: Bandpass spectra of a subset of OCTANE-860 PLC waveguide outputs measured with an optical fiber probe.

3 PACKAGING AND SPECIFICATIONS

Figure 1 shows an image of the OCTANE-860 PLC with the two inputs on the right chip facet and the outputs of both gratings routed to the bottom chip facet. As shown in Fig. 4, the spectrometer takes input light from a 780HP FC/APC fiber which is then sent to a fiber-based polarizing beamsplitter (PBS). Each of the two outputs from the splitter is then sent into the optical module which is the silver enclosure in Fig. 5. The optical module encloses the PLC which has optical fibers coupled to the PLC input and a CMOS linear detector array attached to the chip output.

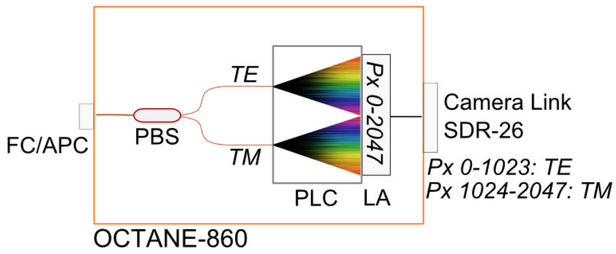


Figure 4: (a) Design schematic showing components of the spectrometer including a polarizing beam splitter (PBS) and a PLC coupled to a linear array (LA) of detector pixels.

The detector is connected to readout electronics which convert the data to a high-speed Camera Link format. The fully packaged prototype unit shown in Fig. 5 has dimensions of 8.5×10.5×2.5 cm and weighs 310 g. The instrument bandwidth is $\Delta\lambda$ = 70 nm centered at λ_0 = 860 nm with a channel spacing of $\delta\lambda$ = 0.068 nm/pixel at 860 nm (27.6 GHz/pixel or 0.92 cm^{-1}/pixel in equal wavenumber spacing). This spectral resolution provides a maximum OCT imaging depth of 2.7 mm in air (n = 1.0) or 2.0 mm in tissue (n = 1.38). The total bandwidth is well-suited for a light source with a full width at half maximum (FWHM) bandwidth of 35 nm to provide an axial resolution of 9.3 µm in air or 6.8 µm in tissue.

Figure 5: Photograph of packaged OCTANE-860 prototype spectrometer shown without internal fiber routing.

4 OCT TEST RESULTS

The OCTANE-860 spectrometer was incorporated into an SD-OCT system (Fig. 6) in order to determine its imaging capabilities. The system consists of an SLD with a 35 nm FWHM bandwidth and a 50/50 broadband fiber coupler which splits the light into a sample arm and a reference arm. Backscattered light from the sample interferes with light from reference arm and is spectrally analyzed with the OCTANE-860 spectrometer.

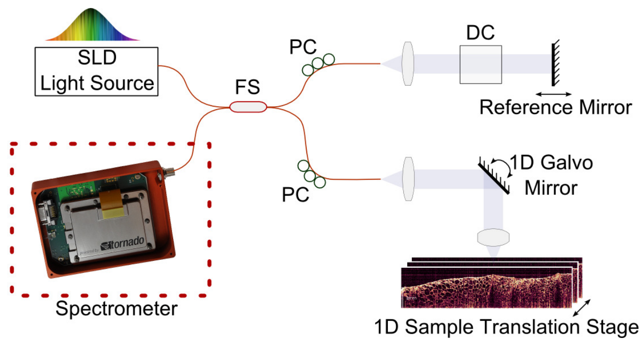


Figure 6: Schematic of an SD-OCT setup using the OCTANE-860 spectrometer. FS: fiber splitter, PC: polarization controller, DC: dispersion compensator.

An example output spectrum from OCTANE-860 is shown in Fig. 7 when a mirror is placed in the sample arm of the SD-OCT setup. The inset shows the processed OCT A-scan for an optical path difference of 0.25 mm between the two arms, demonstrating an axial resolution of 9.6 µm in air. This is close to the theoretical limit of 9.3 µm for the 35 nm bandwidth light source used in this experiment.

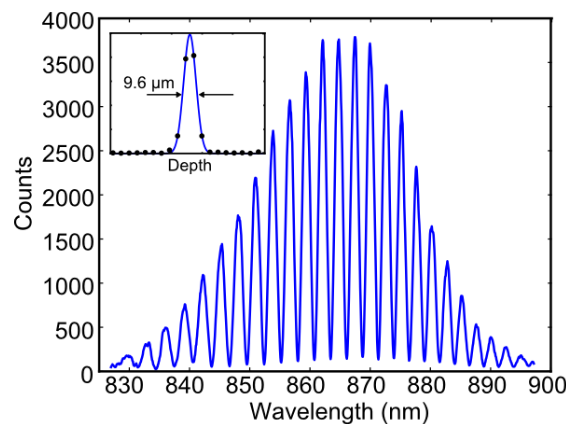


Figure 7: Sample interferogram measured with an OCTANE-860 in an SD-OCT setup with a mirror in the sample arm. Inset shows reconstructed data and curve fitting demonstrating axial resolution of 9.6 µm.

Figure 8 shows the axial resolution and OCT sensitivity as a function of depth in the image for both polarizations. The TE and TM polarizations are measured in two separate experiments by rotating the polarization state of the signal launched into the spectrometer. The axial resolution (triangles) does not degrade with distance which is desired for OCT imaging. The OCT sensitivity (circles) shows a characteristic roll-off for SD-OCT systems. While the system does provide a useable signal throughout the imaging range, the signal level falls off faster than a similar experiment performed with an unpackaged PLC chip. This points towards parasitic crosstalk from the chip packaging as the cause of the roll-off degradation which will be improved in future production units.

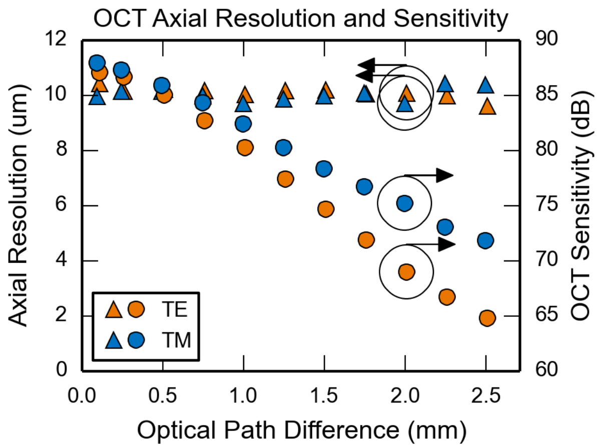
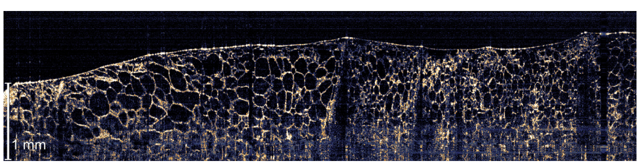


Figure 8: Axial resolution (triangles) and OCT sensitivity (circles) for TE (orange) and TM (blue) polarizations.

We perform a head-to-head comparison between OCTANE-860 and a conventional free-space spectrometer with comparable specifications. The comparison spectrometer uses a volume phase holographic transmission grating (Wasatch Photonics 1008-2) and a high-speed CMOS line-scan camera (Basler Sprint). An OCT image of a grape is shown in Fig. 9(a) using OCTANE-860 and Fig. 9(b) using the conventional spectrometer. Comparable image reconstruction and dispersion compensation are performed on both data sets, and we find that the image quality is very similar.



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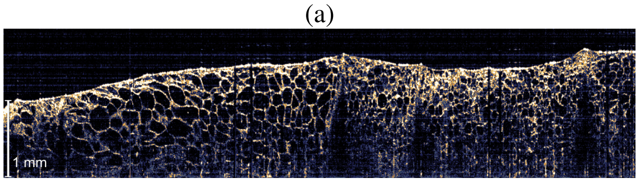

(b)

Figure 9: OCT cross-sectional image of a grape captured with (a) OCTANE-860 and (b) conventional free-space spectrometer.

OCTANE-860 is also suitable for a number of industrial applications for non-destructive testing and quality control. Shown in Fig. 10 are the individual layers within a smartphone LCD screen. The second layer clearly shows the color filter which includes three elements per pixel and highlights the ability of OCT to provide non-destructive 3D volumetric imaging data for thin film manufacturing. Industrial markets for OCT imaging include semiconductor manufacturing, pharmaceuticals, material characterization, printed electronics, and many others.

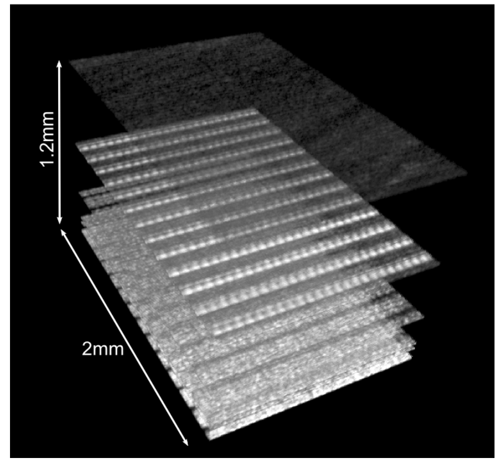

Figure 10: OCTANE-860 SD-OCT image of the layers in a cell phone LCD screen.

5 FUTURE DIRECTIONS

Development of the next iteration of OCTANE will focus on increasing the efficiency of the PLC. The use of a new material platform will result in a polarization-insensitive system to increase the applicability to more OCT applications, as well as increasing the number of output channels to 2048.

Future iterations will seek to add more of the OCT components (Fig. 6) onto the chip and into the package. The overall savings in size and cost will increase dramatically as the level of integration increases, with the ultimate goal of producing handheld OCT systems at a fraction of the cost of current systems.

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