Performance Improvement and Birefringence Investigation of Spectral-Domain Optical Coherence Tomography Using a Modified Arrayed-Waveguide Grating

L. Chang, B.I. Akca, R.M. de Ridder, K. Wörhoff, and M. Pollnau

Integrated Optical Microsystems Group, MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands l.chang@utwente.nl

An arrayed-waveguide grating (AWG) with its high accuracy and stability is a powerful tool for spectral analysis. We investigate its potential for spectral-domain optical coherence tomography (SD-OCT). A silicon-oxynitride-based AWG spectrometer for the 800 nm wavelength range is designed for on-chip SD-OCT systems. By removing the output waveguides of the AWG, the depth range is significantly enhanced. In addition, the effect of polarization dependency of the AWG on sensitivity roll-off is investigated and for partial polarization, a beat effect is observed in the depth ranging measurements, which leads to signal fading at specific depths.

Optical coherence tomography (OCT) [1] is an optical signal acquisition and processing technique which can provide three dimensional images with micrometer-resolution. The measurement principle of OCT is based on low-coherence interferometry (LCI) [2] in which interference patterns due to the superposition of a multitude of waves with a large spread in wavelength is studied. These distinctive patterns enable one to determine the location at which light is reflected back and to measure the depth profile of the scattering amplitude. By performing multiple LCI measurements at different lateral coordinates on a sample, a three-dimensional cross-sectional image of the scattering amplitude can be constructed.

Current state-of-the-art OCT systems operate in the Fourier-domain, using either a broad-band light source with a spectrometer, known as "spectral-domain OCT" (SD-OCT), or a rapidly tunable laser, known as "swept-source OCT" (SS-OCT). Both systems contain a multitude of fiber and free-space optical components which make these instruments costly and bulky. The size and cost of an OCT system can be decreased significantly by the use of integrated optics. A suitable material technology and optimum design may allow one to fabricate extremely compact and low-cost OCT systems.

One of the key components of an SD-OCT system is the high-resolution spectrometer. Although integration of a spectrometer on a chip which has sufficiently good specifications to obtain a good depth range and resolution in OCT image is challenging, AWGs present a well-established way towards miniaturization. A schematic layout of an AWG is shown in Fig. 1. AWGs are ideally suited for applications such as OCT and spectroscopy, with their high spectral resolution, small form factor, large bandwidth, and low insertion loss [3]. Recently, we have demonstrated a depth range of 1 mm and an axial resolution of 19 µm by performing interferometric distance measurements in a fiber-based SD-OCT system with a silicon-oxynitride (SiON) based AWG designed for the 1300 nm wavelength range [4]. However, there are design limitations on resolution and free spectral range (FSR), which restrict the axial resolution and maximum imaging range of SD-OCT systems.

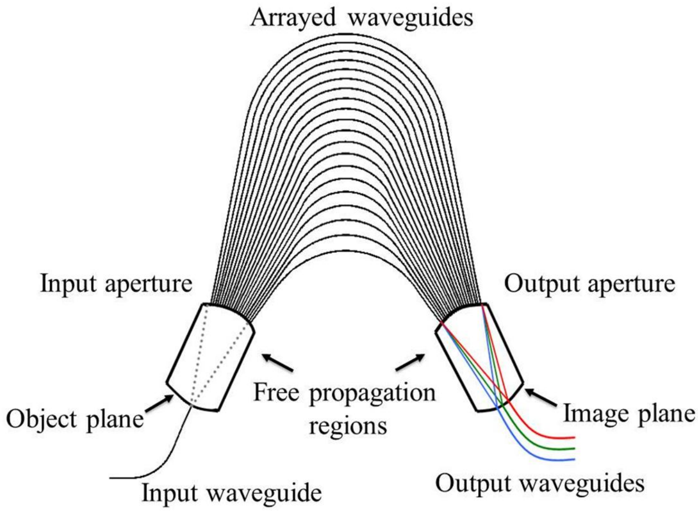

Fig. 1. Schematic layout of an arrayed waveguide grating (AWG).

For obtaining a large depth range, the AWG spectrometer must have a high wavelength resolution, while a high axial resolution requires a wide free spectral range (FSR) [5]. As usually the output spectrum of an AWG is discretized in a number of output channels, the combination of large depth range and high axial resolution requires a large number of output channels, up to a point where space limitations inhibit further improvement. One possible solution is omitting the output channels (or removing them from a conventional AWG by dicing [6]). In this way, the wavelength discretization will be determined by the number of pixels on the camera, which can be much larger than the number of output channels, thus enhancing the depth range significantly.

Another important issue is the polarization dependency of the spectrometers, which affects the sensitivity roll-off. The imaging range of SD-OCT is limited by the sensitivity roll-off, which is the attenuation of the OCT signal due to washout of the interference fringe visibility with increasing depth [5]. Using a less polarization-dependent dispersive element in an OCT system is more favorable. An AWG spectrometer is polarization independent if its array waveguides are polarization independent, which can be achieved by balancing the material and waveguide birefringence [7]. Although this approach requires a highly fabrication-tolerant design, it makes AWGs advantageous over bulky spectrometers. In addition, the cost and size of LCI and OCT systems using polarization-independent AWG spectrometers will reduce significantly by eliminating the components for polarization control.

In this work, we discuss the effect of discrete output channels and polarization dependency of an AWG on the performance of a spectral domain optical low coherence reflectometer (SD-OLCR) and experimentally verify the improvement in depth range when omitting the output channels from the AWG and the modulation effect of polarization on sensitivity roll-off.

For the arrayed waveguides, single-mode SiON channel waveguides with 1.5 μm width and 0.8 μm height were used. The size of each device is optimized by beam-propagation simulations, which resulted in a chip area of 2.6 cm × 2.1 cm.

The Fourier transform of a measured spectrum (with pure transverse-electric (TE) light) by using an AWG with output channels is shown in Fig. 2. The finite sampling rate of the output channels (125 channels) result in five extra peaks. One of them corresponds to the spatial frequency of the output channels and the other four are aliasing peaks. By increasing the depth, the peak corresponding to the real depth information will shift right and will meet the left shifting leftmost aliasing peak at a depth value of about 1 mm, which is halfway the peak position corresponding to the spatial frequency of the output channels. After removing all the output channels by dicing, all five extra peaks are right shifted beyond 3.5 mm and thereby the maximal depth range is not limited by the aliasing peak generated from the output channels and will be increased significantly.

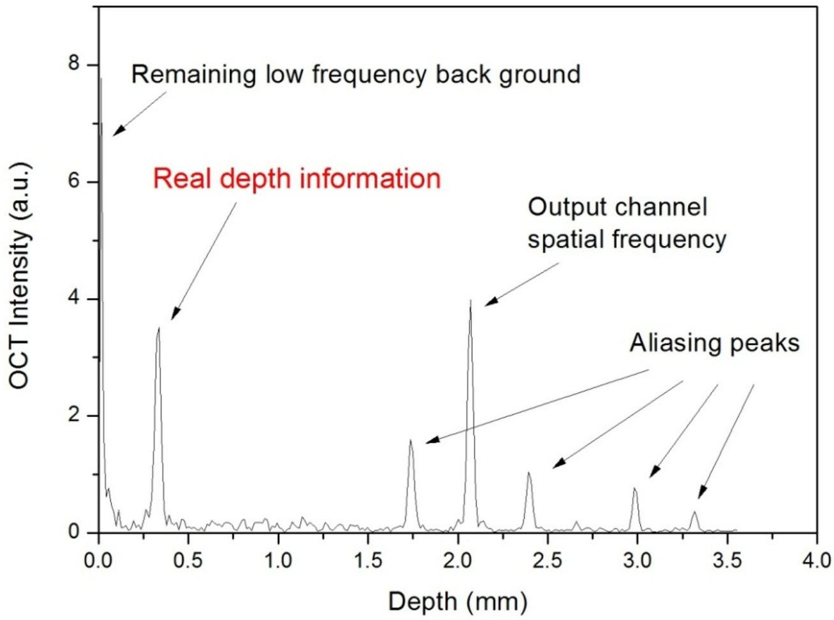

Fig. 2. Fourier transform of a measured spectrum (with pure transverse-electric (TE) light) by using an AWG with output channels.

The depth ranging measurements of the 800-nm AWG with mixed polarized light is given in Fig. 3. The dashed line is the corresponding sensitivity roll-off function. The dip in the roll-off depends on the intensity ratio of TE and TM components of the partial polarized light. When we launched pure TE or TM light into the AWG, the dip disappeared. On the other hand, when the TE and TM light have the same intensity the lowest point in the dip is as low as the background noise.

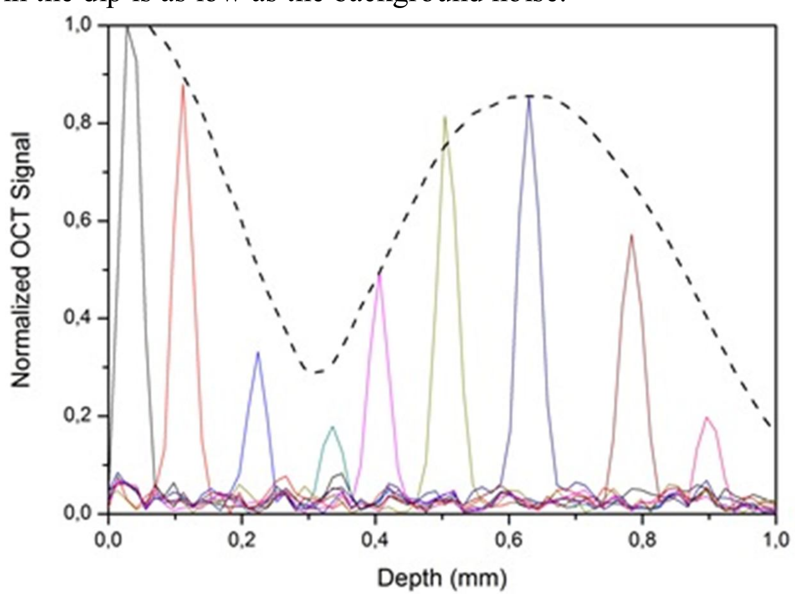

Fig. 3. Measured sensitivity roll-off with a partial polarized incident light.

In conclusion, we have improved the maximal depth range significantly by removing the output channels of the 800-nm AWG. In addition, we have investigated the effect of polarization dependency of the AWG on the OLCR signal, which may show a severe limitation of the attainable depth range. With a proper waveguide design, one can compensate the material birefringence by the waveguide birefringence. This will result in a polarization independent AWG and thereby a polarization insensitive SD-OLCR system.

This work was supported by the Smart Mix Program of the Netherlands Ministry of Economic Affairs and the Ministry of Education, Culture and Science. The authors thank V. Duc Nguyen for providing the band-pass filter, Anton Hollink and Henk A. G. M. van Wolferen for technical support.

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