High-performance Spectral-domain Optical Low-coherence Reflectometry with an Integrated Arrayed-waveguide Grating

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Abstract: The effect of discrete output channels and polarization dependency of an arrayed-waveguide-grating (AWG) spectrometer on spectral-domain optical low-coherence reflectometry performance is investigated. Removing the output waveguides of the AWG enhances the depth range significantly.

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1. Introduction

Optical low-coherence reflectometry (OLCR) [1] is a one-dimensional optical ranging technique for measuring the position of reflective interfaces in a sample. It was first developed for characterization of fiber-based waveguide devices [1]; in the following years the transverse scanning capability made cross-sectional imaging, i.e., optical coherence tomography (OCT), possible [2]. Integrated optics offers enormous cost and size reduction to OLCR and OCT systems. We demonstrated cross-sectional imaging of a multilayered phantom by use of an arrayed-waveguide-grating (AWG) spectrometer in a spectral-domain (SD) OCT system [3], proving that AWG spectrometers with their high spectral resolution and compactness [4] are excellent candidates for on-chip SD-OLCR and SD-OCT systems.

However, polarization dependency and discrete output channels of an AWG spectrometer limit the performance of these integrated systems. Polarization dependency of AWG spectrometers affects the sensitivity roll-off, which results in signal fading at specific depth points. An AWG spectrometer is polarization independent, if its array waveguides are polarization independent, which can be achieved by balancing the material and waveguide birefringence. Discrete output channels of the AWG spectrometer limit the maximum depth range. A possible solution is omitting the output channels or removing them from a conventional AWG by dicing [5]. 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.

2. Experimental setup

A schematic of the SD-OLCR system with an AWG spectrometer is shown in Fig. 1. The free-space Michelson interferometer is illuminated with a broadband light source which is band-pass filtered (bandwidth = 9.4 nm) in order to prevent overlap of different spectral orders of the AWG. The light returning from the two arms is combined and focused by an objective lens into a fiber coupler with a 10/90 splitting ratio. A Ti:Sapphire laser is connected to the other input port of the coupler to be used in the polarization measurements. 90% of the light returning from the two arms is coupled into the AWG by a free-space coupling arrangement, which consists of two objective lenses and a polarizer. The same AWG as investigated in Ref. [3], with a center wavelength of 800 nm, a free spectral range

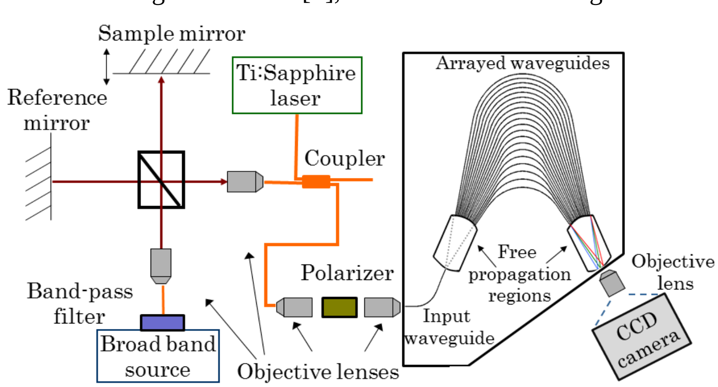

Fig. 1. Schematic of the experimental set-up used for SD-OLCR with an AWG. (without output channels).

(FSR) of 19.4 nm, and a wavelength resolution δλ of 0.16 nm, is used in this work. The output channels of the AWG have been removed in order to increase the maximal depth range. The light dispersed in the arrayed waveguides is imaged by a microscope objective lens (NA = 0.12) onto the CCD (512 detector pixels).

3. Measurements and Results

The effect of partial light polarization on sensitivity roll-off was investigated for a TE/TM power ratio of 1. The single-wavelength response of the AWG for partial polarization is given in the inset of Fig. 2a. The AWG was not designed to be polarization independent; consequently, a spectral shift of 0.5 nm was measured between TE and TM polarizations [3]. A polarization-dependent AWG images a spectral peak at a given wavelength onto different positions for TE and TM polarizations. The measured interference spectrum is the convolution of the real interference spectrum and the single-wavelength response of the AWG. The depth information is modulated by the Fourier transform of the single-wavelength response (red dashed line). This modulation leads to signal fading at certain depth and, thus, low signal-to-noise ratio at the corresponding position.

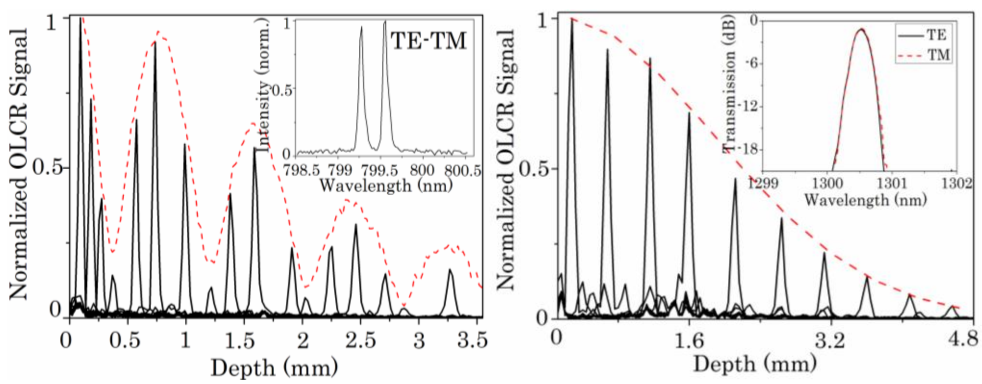

Fig. 2. a) Measured OLCR signal versus depth and roll-off (dashed line) with the 800-nm polarization-sensitive AWG for unpolarized light (TE/TM = 1). The inset is the single-wavelength response of the AWG for TE/TM = 1. **b)** Measured OLCR signal with the 1.3-µm polarization-insensitive AWG..

As a proof-of-concept, a non-birefringent AWG centered at 1300 nm was designed with δλ = 0.4 nm, resulting in 1 mm of depth range, and FSR = 20 nm. Silicon oxynitride channel waveguides with a width of 2.2 µm, height of 1 µm, and core refractive index of 1.52 were fabricated. No significant polarization-dependent shift was observed in the transmission measurements for the center and outer channels, as shown in the inset of Fig. 2b. The output channels were removed by dicing and the OLCR measurements for partial polarization (TE/TM = 1) were performed using the set-up shown in Fig. 1 with an infrared camera (320 pixels). An improved depth range of 4.6 mm was obtained by removing the output channels and no beat effect was observed, as shown in Fig. 2b.

4. Conclusions

We have improved the depth range of an SD-OLCR system using an integrated AWG to the level of existing bulk commercial systems by removing the output waveguides of the AWG. In addition, the effect of polarization on sensitivity roll-off has been investigated. A beat effect has been observed in the roll-off curve for partial polarization, which leads to signal fading at specific depths. As a permanent solution to polarization-related signal fading, a polarization-independent AWG has been designed and no beat effect has been observed in depth ranging measurements for partial polarization. Such a solution would eliminate the need for polarization control with its associated noise and cost penalties in OCLR and OCT systems.

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5. References

[1] R. C. Youngquist, S. Carr, and D. E. N. Davies, Opt. Lett. 12, 158 (1987).
[2] D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, Science 254, 1178 (1991).
[3] B. I. Akca, V. D. Nguyen, J. Kalkman, N. Ismail, G. Sengo, F. Sun, T. G. van Leeuwen, A. Driessen, M. Pollnau, K. Wörhoff, and R. M. de Ridder, "Toward spectral-domain optical coherence tomography on a chip", IEEE J. Sel. Top. Quantum Electron., doc. ID 10.1109 (posted 6 October 2011, in press).
[4] M. K. Smit and C. van Dam, IEEE J. Sel. Top. Quantum Electron. 2, 236 (1996).
[5] N. Cvetojevic, J. S. Lawrence, S. C. Ellis, J. Bland-Hawthorn, R. Haynes, and A. Horton, Opt. Express **17**, 18643 (2009).