Polarization-Independent Optical Low-Coherence Reflectometry with a Non-Birefringent Arrayed-Waveguide Grating

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***Abstract*—The polarization dependency of an arrayed-waveguide grating (AWG) in an optical low-coherence reflectometry system is investigated. For mixed polarization, signal fading is observed at specific depths. This fading is eliminated by using a non-birefringent AWG.**

Keywords-arrayed waveguide grating; Non-Birefringent waveguides; Optical Low-coherence Reflectometry

I. INTRODUCTION

Optical low-coherence reflectometry (OLCR) is a one-dimensional optical ranging technique where the amplitude and the time delay of backscattered light from different depths in a sample is resolved using multi-wavelength interferometry. It was developed about 20 years ago [1], and has since become a widely-used tool for measuring optical reflectivity as a function of distance. Combining OLCR systems with transverse scanning of the probe beam resulted in optical coherence tomography (OCT) [2]. The size and cost of an OLCR system can be decreased significantly through the use of integrated optics. 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 [4] are excellent candidates for on-chip SD-OLCR and SD-OCT systems.

The polarization dependency of the spectrometers used in SD-OLCR systems affects the sensitivity roll-off with depth. For controlling the polarization state of the light, extra components are needed which increase the size and cost of the SD-OLCR systems. In this sense, it is more favorable to use a non-birefringent AWG spectrometer in an SD-OLCR system. An AWG spectrometer is polarization independent if its array waveguides are polarization independent, which can be achieved by balancing the material and waveguide birefringence [5]. Although this approach requires a highly fabrication-tolerant design, it makes AWGs advantageous over bulky spectrometers.

In this work, we first discuss the impact of polarization dependency of an AWG on SD-OLCR performance. The modulation effect of polarization on sensitivity roll-off in depth is experimentally verified. Secondly, a polarization-independent AWG is demonstrated as a permanent solution to the polarization-related signal fading problems.

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II. BIREFRINGENT AWG SPECTROMETER

An optical waveguide is birefringent, if it exhibits different effective refractive indices for TE and TM polarized light. For a birefringent AWG, the phase delay difference between two adjacent waveguides is different for TE and TM polarized light (for each single wavelength). This phase delay difference leads to a phase front angle difference between TE and TM polarized light at the second free propagation region (FPR). Thus, TE and TM polarized light focus onto different positions at the end of the second FPR.

The spectrum $M(k)$, with k the wavenumber, as measured by a spectrometer is the convolution of the real input spectrum $R(k)$ with the single-wavelength response function (SWRF) $S_{k0}(k)$ of the spectrometer. Preferably, $S_{k0}(k)$ should exhibit a single peak which is as narrow as possible. In case of a birefringent AWG with a mixed polarization input, the SWRF is a double-peak function due to the different focal positions of the TE and TM polarized light. The double-peak SWRF leads to a signal fading problem in the SD-OLCR applications. The SD-OLCR signal $D(z)$ is obtained by taking the Fourier transform (FT) of the measured spectrum, which is equal to the FT of the real spectrum times the FT of the SWRF:

$$D(z) = F_{k\to z}\{M(k)\} = F_{k\to z}\{R(k)\}\cdot F_{k\to z}\{S_{k0}(k)\}. \quad (1)$$

If each peak of $S_{k0}(k)$ can be approximated as a Gaussian, Fourier transforming the double peak SWRF results in

$$|F_{k\to z}\{S_{k0}(k)\}| = \sqrt{1+2a(a-1)[1-\cos(2\pi\Delta kz)]}\cdot|F(z)|, \quad (2)$$

where $F(z)$ is a Gaussian, a and $1-a$ are the percentage of TE and TM intensities respectively, Δk is the wavenumber distance of the two peaks of $S_{k0}(k)$, and z is the depth coordinate. The cosine term in (2) represents a beating effect, of which the spatial frequency is Δk, which depends on the refractive index difference $\Delta n_{TE\text{-}TM}$ of the TE and TM polarized light in the arrayed waveguide region. One way to weaken the beating effect in SD-OLCR signal is reducing $\Delta n_{TE\text{-}TM}$ so far that the beating frequency becomes low enough to push the first beating valley beyond the maximum depth range.

III. 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 in order to prevent overlap of

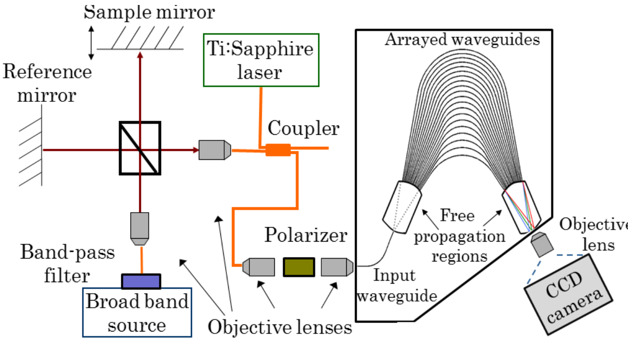

Figure 1. Schematic of the experimental set-up

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 AWG SWRF 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 an adjustable polarizer. Two AWGs were used in this work, a birefringent AWG centered at 800 nm [6], and a non-birefringent AWG centered at 1300 nm. The output channels of the AWG were 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.

IV. Measurements and Results

The effect of mixed polarization on sensitivity roll-off was investigated for a TE/TM power ratio of 1. The SWRF of the AWG for mixed polarization is given in the inset of Fig. 2 and Fig. 3.

A birefringent AWG (Fig. 2) images a spectral peak at a given wavelength onto different positions for TE and TM polarizations. The depth information is modulated by the FT of the SWRF (dashed line). This modulation leads to signal fading at certain depth and, thus, low SNR at the corresponding position.

As a proof-of-concept, a non-birefringent AWG centered at 1300 nm was designed. Silicon oxynitride channel waveguides

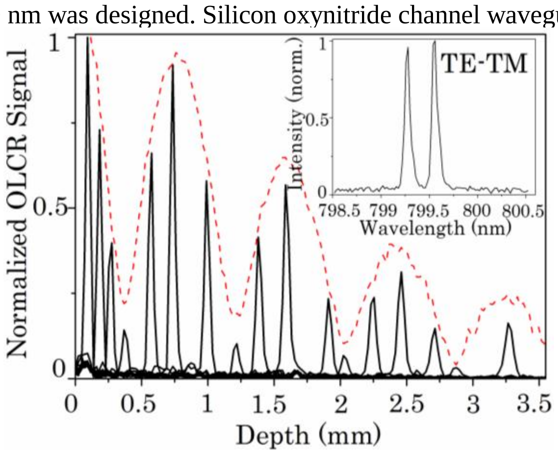

Figure 2. Measured OLCR signal versus depth and roll-off (dashed line) with the 800-nm birefringent AWG for mixed polarized light (TE/TM = 1). The inset is the SWRF of the AWG for TE/TM = 1.

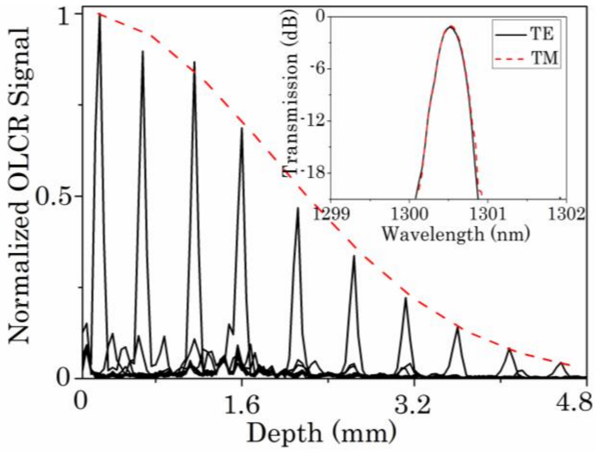

Figure 3. Measured OLCR signal with the 1.3-µm non-birefringent AWG. The inset is the SWRF of the AWG for TE/TM = 1.

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, as shown in the inset of Fig. 3. The OLCR measurements for mixed polarization (TE/TM = 1) were performed using the set-up shown in Fig. 1 with an infrared camera (320 pixels). No beating effect was observed within the maximum depth range, as shown in Fig. 3.

V. CONCLUSIONS

The effect of polarization on sensitivity roll-off has been investigated. For a mixed polarization, signal fading was observed at specific depths. The use of a non-birefringent AWG eliminated this fading completely, as no beating effect for mixed polarization has been observed within the maximum depth range. Such a solution would eliminate the need for polarization control with its associated noise and cost penalties in OCLR systems.

VI. REFERENCES

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