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Polarization in Low Coherence Interferometry

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Abstract—**The polarization mismatch of the sample and reference arms in optical fiber based low coherence interferometry has critical effect on its depth resolution when the light source is partially polarized: When the polarization states of the two arms are matched the measured point spread function (PSF) is almost identical to the theoretical prediction; When their polarization states are mismatched the PSF can be so distorted that the depth resolution is degraded to several times of the theoretical value. When the source light is polarized the depth resolution becomes independent of the polarization mismatch.**

I. Introduction

Low coherence interferometry (LCI) is a widely used sensing and imaging technology for biological tissues, which can reveal the microscopic structures of biological samples. As a branch of LCI, optical coherence tomography (OCT) has been used in imaging of various biological tissues with the most successful in imaging the eye. Both time domain (TD) and spectral domain (SD) detection techniques have been applied in LCI with great success. As in all imaging modalities, resolution is an important parameter that describes the spatial resolving capability of a system. Ultra-high resolution OCT has been demonstrated in both TD and SD systems. By using either superluminescent diode (SLD) or femtosecond laser based light sources, depth resolution better than 3 μm in the tissue has been achieved [1–3]. We all know that the depth resolution of a LCI system depends on the bandwidth and the center wavelength of the light source if the spectra and dispersion of the reference and sample arms in the interferometer are well balanced [2,4,5]. In biological tissues, scattering and birefringence can modify the polarization states of the incident sample light [6–8] in addition to the polarization modification by the single mode optical fibers in the sample and reference arms. Polarization controllers are usually used in a fiber based LCI to optimize an image by changing the amplitude and orientation of birefringence in the sample or reference fiber. However, the effect of polarization mismatch on the resolution of a fiber based LCI has not been reported.

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II. Experiments and Results

A. Experimental system

A schematic of the configuration of the LCI system is shown in Fig.1, which is the same as in our previous publications [9] except that we didn't use optical scanner in the sample arm for the experiments. A three-module SLD (Broadlighter, T840-HP, Superlumdiodes Ltd, Moscow, Russia) with a center wavelength of 840nm and a FWHM (full width at half maximum) bandwidth of 100 nm was used. The low coherence light first passed through a fiber-based isolator (IO-F-850-FC/APC2, OFR) and was coupled into a fiber based Michelson interferometer that consists of a 2×2 3dB fiber coupler, which split the light into the reference and the sample arms. In the reference arm a lens was used to focus the light onto a mirror. In the sample arm an identical lens was used to focus the light either on a mirror or a sample. Polarization controllers were used in both arms to modify the corresponding light polarization states. In the detection arm, the same spectrometer and image acquisition system as in our previous publications [9] were used to detect the combined reference and sample light and to process the OCT signal.

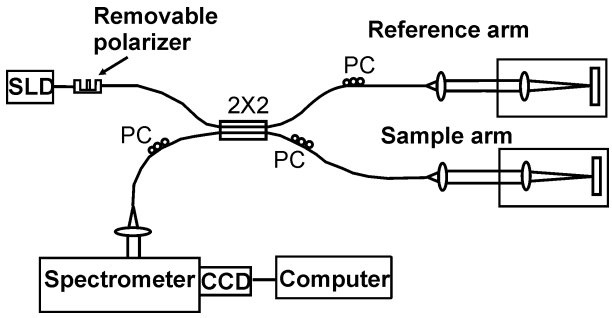
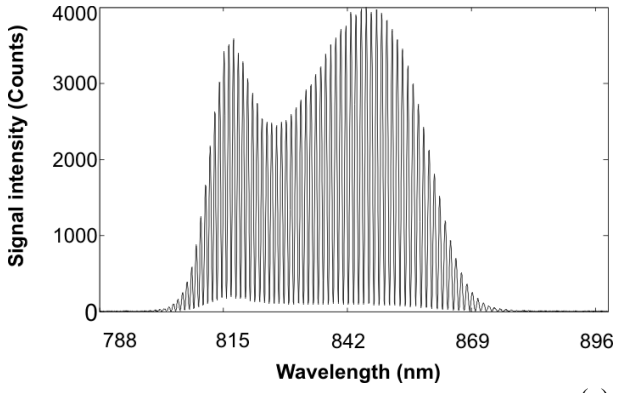


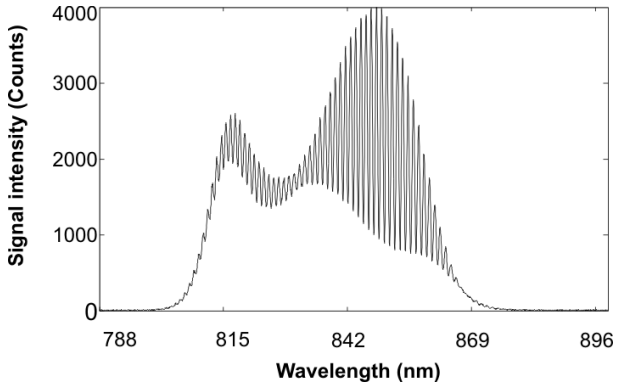
Fig. 1. Schematic of the experimental system. PC: polarization controller.

B. Experimental results

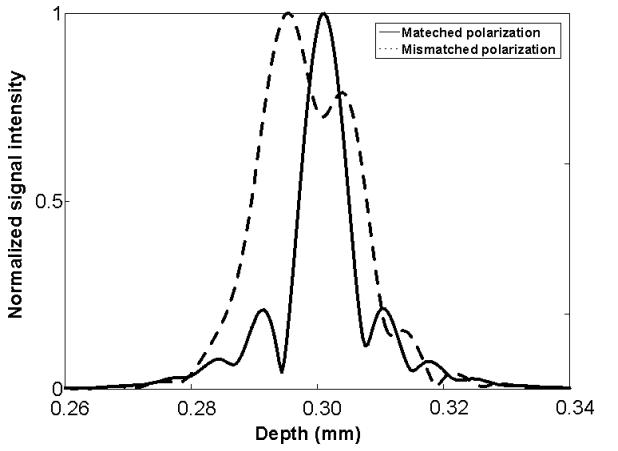
To test the polarization effect on the depth resolution, a mirror was first placed in the sample arm. When we adjusted the polarization controller to vary the polarization state of the reference or the sample arm, we found that the spectral interference pattern changed significantly. When the polarization states of the two arms are matched, the point spread function (PSF has a main single peak with a FWHM width of 3.8 μm (the depth resolution of OCT in air). In the



(a)



(b)



(c)

Fig. 2. Measured interference spectra and PSF for a mirror for a single partially polarized SLD: (a) the polarization states of the two arms were matched; (b) the polarization states of the two arms were significantly unmatched; (c) PSF calculated from the interference spectra in (a) and (b).

case when the polarization states of the two arms are significantly mismatched, the PSF has multiple peaks with comparable amplitudes and the calculated FWHM width is around 19 μm, which is a 400% increase over the best case. When measuring the PSF ate different polarization matching conditions, if the amplitudes of the side lobes are lower than half of that of the main peak, only the width of the main peak was counted. Otherwise, multiple peaks were included. In the experiments we found that the worse the polarization mismatch the more the PSF is distorted with increasing amplitude of the side lobes.

To test the dependence of the resolution distortion on the bandwidth of the light source we repeated the experiments with only one SLD by turning the other two SLDs off. The test results are shown in Fig.2. In the best situation, when the polarization states of the two arms were matched, the depth resolution is 6 μm. In the worst situation the measured depth resolution is 15 μm, which is 150% over the best situation. We can see that the broader the bandwidth of the light source the more sensitive the depth resolution is to the polarization mismatch of the two arms.

III. ANALYSES AND DISCUSSION

We hypothesize that the distortion of the PSF is caused by the polarization property of the light source. The measured DOPs of the light after passing through the isolator were 0.49 and 0.74 for the 3 SLDs and single SLD, respectively. So the light sources are partially polarized, in which the polarization states of light at different wavelengths are different. The polarization states of the sample and reference light at the detector at a certain wavelength can be expressed as [8]

$$\begin{aligned} \mathbf{S}_{out,s}(\lambda) &= \mathbf{M}_g \mathbf{M}_d \mathbf{M}_{rs} \mathbf{M}_s \mathbf{S}_{in}(\lambda) \\ \mathbf{S}_{out,r}(\lambda) &= \mathbf{M}_g \mathbf{M}_d \mathbf{M}_{rr} \mathbf{M}_s \mathbf{S}_{in}(\lambda), \end{aligned} \tag{1}$$

where $\mathbf{S}_{in}$, $\mathbf{S}_{out,s}$, and $\mathbf{S}_{out,r}$ are the incident, and output Stokes vectors of the sample and reference light at wavelength λ, respectively; $\mathbf{M}_s$, $\mathbf{M}_{rs}$, $\mathbf{M}_{rr}$, $\mathbf{M}_d$, and $\mathbf{M}_g$ are the Mueller matrix of the fiber in the source arm, the roundtrip Mueller matrix of the sample arm, the roundtrip Mueller matrix of the reference arm, and the Mueller matrices of the detection arm and the grating in the spectrometer, respectively. We can see that when we adjust the polarization controller the matching conditions between the reference and sample polarization states vary with wavelengths. As a result, when the polarization states at certain wavelengths are matched they may be mismatched at other wavelengths, like in the situation shown in Fig.1b. The non-uniform variation of the polarization matching across the wavelengths gives rise to the distortion of the PSF. From Eq. 1, we can see that if we polarize the source light, different wavelengths coming from the same arm have the same polarization state at the detector, i.e. $\mathbf{S}_{out,s}$ and $\mathbf{S}_{out,r}$ are wavelength independent. As a result, adjusting a polarization controller the matching conditions between the reference and sample polarization states are identical across the wavelengths, so that the depth resolution should be insensitive to polarization mismatch.

To test the hypothesis we polarized the source light by using a linear polarizer (PCB-2.5-830, OFR) before it was coupled into the source arm of the fiber beam splitter. The measured DOP=0.9998. The test results are shown in Fig.3.

From the test results we can see that by polarizing the source light the depth resolution is maintained at various polarization matching conditions between the reference and sample arms with only slight changes of the profiles of the side lobes. The test results proved our hypothesis.

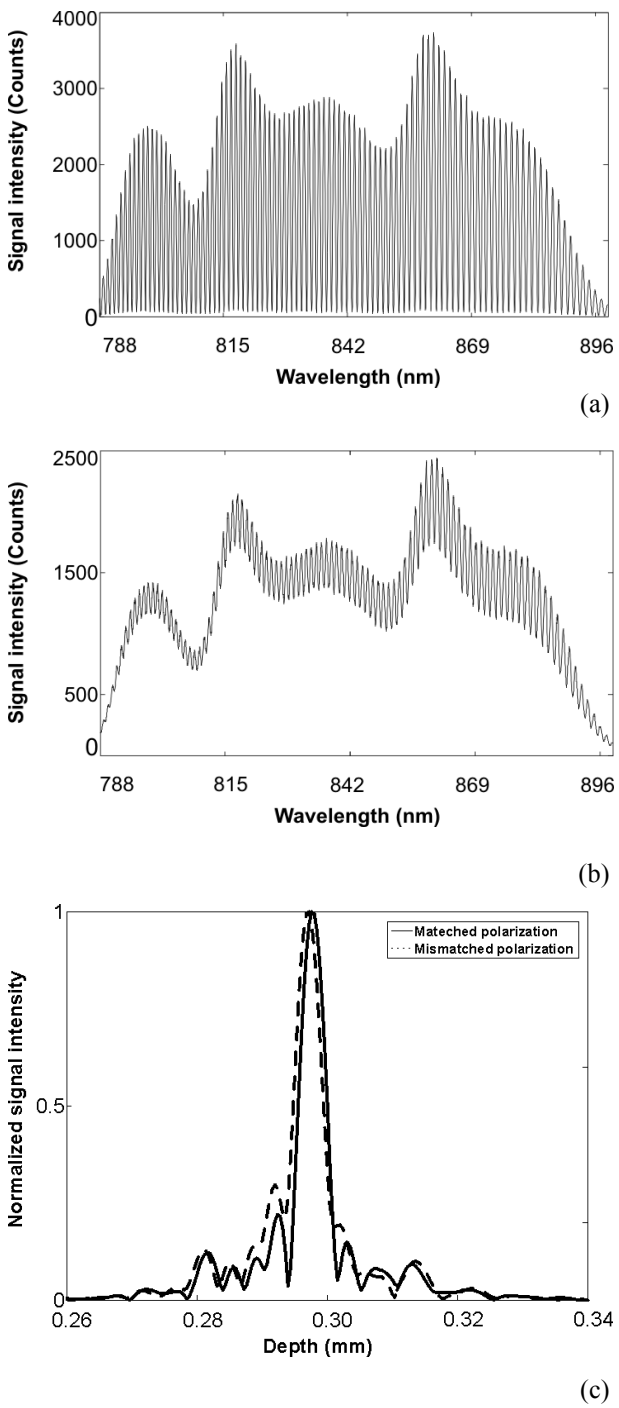


Fig. 3. Measured interference spectra and PSF for the light source in Fig.1 after the light was polarized with a polarizer: (a) the polarization states of the two arms were matched; (b) the polarization states of the two arms were significantly unmatched; (c) PSF calculated from the interference spectra in (a) and (b).

We also tested our hypothesis by imaging a scattering and birefringent tape sample with polarized and partially polarized source light (the original SLD), respectively. The sample was placed on the focal plane of the lens in the sample arm. For each polarization status of the light source we adjusted the polarization controller in the reference arm to optimize the sharpness of the peak at the front surface of the tape. We found that the shape and sharpness of the OCT signals at the front surface is similar for the partially polarized and polarized light (FWHM=3.8μm). But the two signals at the back surface of the tape differed with each other significantly. In the case of partially polarized light, the resolution at the back surface was degraded significantly (FWHM=11μm) with greatly increased side lobes. In contrast, for the polarized light, the shape and resolution of the OCT signal is well preserved (FWHM=4.2μm).

The current findings are important in OCT applications in biomedical imaging especially for ultra-high resolution systems. We know that scattering and tissue birefringence can modify the polarization states of the incident sample light.[6] If the source light is partially polarized (DOP<1), modification of the sample light polarization state will seriously degrade the depth resolution as demonstrated in the test with the tape sample. Because the modification of the polarization states varies along the depth of a sample, adjusting the polarization controller can only compensate the polarization mismatch at a certain depth of the sample with the reference arm, for example the front surface of the sample. In other words, it is impossible to have a uniform depth resolution along the sample depth for partially polarized light source. The problem can be solved by polarizing the source light.

IV. CONCLUSION

In conclusion, we have discovered for the first time that the polarization mismatch of the sample and reference arms in single mode optical fiber based OCT has critical effect on its depth resolution when the light source is partially polarized. We have proved that this effect is caused by the variation of polarization states among different wavelengths of the light source. With partial polarization of the light source the depth resolution of OCT can be quickly degraded by either scattering or birefringence in the sample. By adjusting the polarization states in the reference or sample arm with polarization controller can only improve the depth resolution at certain depth in a scattering or birefringent sample. To achieve uniform resolution along the depth of a sample the light source should be polarized. This discovery is important for high resolution OCT imaging of biological tissues.

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