Polarization management to mitigate misalignment-induced fringe fading in fiber-based optical coherence tomography

Wang, Nanshuo; Liu, Xinyu; Xiong, Qiaozhou; Xie, Jun; Chen, Shi; Liu, Linbo

2017

Wang, N., Liu, X., Xiong, Q., Xie, J., Chen, S., & Liu, L. (2017). Polarization management to mitigate misalignment-induced fringe fading in fiber-based optical coherence tomography. *Optics Letters*, 42(15), 2996-2999.

<https://hdl.handle.net/10356/86957>

<https://doi.org/10.1364/OL.42.002996>

© 2017 Optical Society of America (OSA). This paper was published in *Optics Letters* and is made available as an electronic reprint (preprint) with permission of Optical Society of America (OSA). The published version is available at: [<http://dx.doi.org/10.1364/OL.42.002996>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 21:01:21 SGT

Optics Letters

Polarization management to mitigate misalignment-induced fringe fading in fiber-based optical coherence tomography

NANSHUO WANG,^{1,†} XINYU LIU,^{1,†} QIAOZHOU XIONG,¹ JUN XIE,¹ SHI CHEN,¹ AND LINBO LIU^{1,2,*}

¹School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

²School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 637459, Singapore

*Corresponding author: liulinbo@ntu.edu.sg

Received 17 May 2017; revised 2 July 2017; accepted 3 July 2017; posted 5 July 2017 (Doc. ID 296067); published 27 July 2017

In fiber-based optical coherence tomography (OCT), the interference fringes suffer from the fading effect due to misalignment of the light polarization states between the reference and sample arms, resulting in sensitivity degradation and image intensity variation. We theoretically and experimentally analyzed the relation between the misalignment and the fading coefficient. Assuming that the variation of the light polarization in single-mode fiber (SMF) was a random process, we statistically quantified the fading effect. Furthermore, in OCT configuration based on the Michelson interferometer, we reported an interesting observation that the polarization states of light traveling a round-trip in SMF are not evenly distributed on the Poincare sphere. Based on this observation, we demonstrated the existence of an optimal output polarization state of the reference arm to mitigate the fading effect. We demonstrated that in an optimal setup, the statistical average signal-to-noise ratio could be 3.5 dB higher than a setup without proper polarization management. © 2017 Optical Society of America

OCIS codes: (170.4500) Optical coherence tomography; (060.2430) Fibers, single-mode; (170.3880) Medical and biological imaging.

<https://doi.org/10.1364/OL.42.002996>

Flexible fiber-optic-based imaging probes, including a hand-held scanning head, medical-compatible endoscopes, and intravascular catheters have significantly broadened the clinical application scope of optical coherence tomography (OCT), enabling high-resolution imaging of several regions in the human body. A typical fiber-optic probe contains a single-mode fiber (SMF) cable of several meters' length, to deliver the probing light to the region of interest and return the light backscattered from the tissue structures. SMF provides OCT probes with a high degree of flexibility. Furthermore, circumferential or linear scanning can be achieved with an actuator at the proximal end, such as an optical rotary junction and pull-back translation stage, by mechanically conveying the scanning motion from the proximal end to the imaging spot through the probe structure [1].

Light propagating in SMF is supported by two orthogonal polarization modes [2]. Due to the asymmetries of fiber geometry and stress, such as elliptical cross-sections, bending and twisting, the light of two polarization modes travels at different phase velocities, resulting in the presence of fiber birefringence. Thus, in OCT probes, the polarization states of light at the output of SMF are unpredictable and very sensitive to probe motion [3]. The scanning and flexing of the OCT probes results in variations in the polarization states of light from the sample arm [3]. When the polarization states of light from the sample are misaligned with those of the reference arm, the interference fringes would fade out, leading to intensity variations and signal-to-noise ratio (SNR) degradation in OCT images [4].

Early OCT devices used Faraday rotators to compensate for the birefringence of the round-trip SMF [5], which is impossible to be integrated into a miniature probe. Polarization diversity detection (PDD), usually using two sets of detectors, respectively, aligned with two orthogonal polarization directions, can thereby eliminate the fringe fading effect [4]. However, the PDD scheme of current polarization sensitive OCT (PS-OCT) increases the system complexity and cost. Particularly for spectral-domain OCT systems, PDD needs two pixel-aligned, synchronized spectrometers, tremendously increasing the cost of the entire setup. Besides the PDD approach, common path probe is free of the fading problem [6], which relies on the advance of micro-optics to integrate the reference reflector into the probe distal end.

In this Letter, from the statistical view, we characterized the intensity fluctuation and average SNR loss induced by the fringe fading of the sample arm polarization randomization. By taking advantage of an interesting observation that the output polarization states of a round-trip sample arm SMF are not uniformly distributed on the Poincare sphere [7], an optimum polarization state of reference arm can be found for the Michelson-type OCT configuration. From our analysis, we also suggested that the light source with a low degree of polarization (DOP) such as a supercontinuum source, or light source with long fiber, should be carefully managed to achieve the optimal SNR, which is consistent with previous observations [8]. We demonstrated that our optimal polarization management, using

two additional polarizers, could statistically provide a 1.5 times increase in fringe amplitude, corresponding to 3.5 dB increase in system sensitivity.

Figure 1(a) shows the scheme of a fiber-coupler based OCT setup. Assuming a fully polarized light source and neglecting the polarization mode dispersion (PMD), we have $\mathbf{j}_{\text{ref}} = \mathbf{J}_{\text{out}}^T \mathbf{J}_{\text{ref}} \mathbf{J}_{\text{in}}$ and $\mathbf{j}_{\text{sam}} = \mathbf{J}_{\text{out}}^T \mathbf{J}_{\text{sam}} \mathbf{J}_{\text{in}}$, where the superscript T stands for transpose operation. $\mathbf{j}_s$, $\mathbf{j}_{\text{ref}}$, and $\mathbf{j}_{\text{sam}}$ are the Jones vectors of the input light, the parts of the output light from the reference arm and sample arm, respectively. $\mathbf{J}_{\text{in}}$, $\mathbf{J}_{\text{ref}}$, $\mathbf{J}_{\text{sam}}$, and $\mathbf{J}_{\text{out}}$ are the single-trip Jones matrices of the four-fiber tails of the coupler, labeled in Fig. 1(a). $\mathbf{J}_{\text{tis}}$ is the round-trip Jones matrix of the tissue. According to [9], $\mathbf{J}_{\text{tis}} = \int \chi(z) [e^{i2kn_z z} 0; 0 e^{i2kn_z z}]^T dz$, where $\chi(z)$ is the scattering profile along the depth z . In the context of a non-PS-OCT, the tissue is assumed to be non-birefringent. Taking $n_o = n_e = n$, $\mathbf{J}_{\text{tis}}$ is degenerated to an identity matrix with a factor $F = \int \chi(z) e^{i2kn_z z} dz$. The detected complex fringe $f(k)$ after background subtraction can be written as

$$f(k) = \mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{sam}} = (\mathbf{J}_{\text{out}}^T \mathbf{J}_{\text{ref}} \mathbf{J}_{\text{in}})^\dagger (\mathbf{J}_{\text{out}}^T \mathbf{J}_{\text{sam}} (F(k) \mathbf{I}) \mathbf{J}_{\text{sam}} \mathbf{J}_{\text{in}}) = \mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{mirror}} F(k), \quad (1)$$

where $\mathbf{j}_{\text{mirror}}$ is the Jones vector of the light polarization state when the sample is a single reflector. The superscript $\dagger$ is the conjugate transpose. The measured depth profile can be obtained by the inverse Fourier transform of $F(k)$. $\mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{mirror}}$ is a complex number; thus, Eq. (1) can be written in the form of

$$f(k) = P \exp(i\psi) F(k). \quad (2)$$

From Eq. (2), the polarization state misalignment between the reference and sample arms adds a fading coefficient P and

Fig. 1. (a) Schematic of a fiber-coupler based OCT setup. (b) Stokes representation of the misalignment of the reference and sample polarization states on the Poincare sphere. (c)–(e) Three fading cases with different A , where A is the angle between the polarization states of reference $\mathbf{s}_{\text{ref}}$ and sample $\mathbf{s}_{\text{mirror}}$ (a mirror) on the Poincare sphere. F_x and F_y were simulated fringes obtained from two spectrometers (SP X and SP Y), $F_x + F_y$ was a simulation of fringe if using a single spectrometer (Single SP). SP, spectrometer; PBS, polarizing beam splitter.

a phase ψ to the complex interference fringe. Transforming the Jones vectors $\mathbf{j}_{\text{ref}}$ and $\mathbf{j}_{\text{sam}}$ to their Stokes representations $\mathbf{s}_{\text{ref}}$, and $\mathbf{s}_{\text{mirror}}$, we found

$$P = \cos(A/2), \quad (3)$$

where A is the angle between $\mathbf{s}_{\text{ref}}$ and $\mathbf{s}_{\text{mirror}}$ on the Poincare sphere, indicated in Fig. 1(b). It is more straightforward to interpret the fading effect by the misalignment angle A in the Stokes representation, shown in Figs. 1(b)–1(e) with several specific cases: no fading [Fig. 1(c)], half-fading [Fig. 1(d)], and full fading [Fig. 1(e)].

The reference arm is usually stationary, making $\mathbf{s}_{\text{ref}}$ a fixed point on the Poincare sphere. While in a flexible probe system, $\mathbf{s}_{\text{mirror}}$ is constantly changing during the scanning. For different A-lines, the fading coefficient P is random. From the statistical view, the statistical distribution of P determines the average SNR loss induced by the fading effect.

A white light Michelson-type interferometer with PDD shown in Fig. 2(a) was built to study SMF-induced polarization randomization. Light from a supercontinuum source was modified to be circular polarized after passing through a polarizer (P1) and a quarter-wave plate (QWP), and then was divided into two beams, focused into the reference and sample arms, respectively. Each arm contained an identical 1.5 m long SMF cable and a back-reflector to balance the material dispersion between the two arms. By inserting a 45° polarizer (P2) before the reference arm fiber, the birefringence effect of the reference arm was eliminated. To simulate a flexing probe, a three-paddle polarization controller (PC, Thorlabs, FPC030) was used to randomly twist and bend the sample arm SMF. The interference fringes at two orthogonal polarization directions, $F_x(k)$ and $F_y(k)$, were recorded by two carefully aligned customized spectrometers, responding to a wavelength band of 680–900 nm. Borrowed from the PMD measurement methodology of PS-OCT [10], the Jones vector $\mathbf{j}_{\text{mirror}}(k)$ along the wavelength of the round-trip sample light can be measured as $[\mathcal{H}[F_x(k)] \ \mathcal{H}[F_y(k)]]^T$, where $\mathcal{H}[\cdot]$ is the Hilbert transformation. To mimic the output of a non-PS-OCT, we directly

Fig. 2. (a) Setup for the measurement of the round-trip SMF polarization randomization. (b) Measured fading coefficient P against $\cos(A/2)$; (c) measured DOP distribution. (d) Measured DGD distribution and theoretical Rayleigh PDF. QWP, quarter-wave plate; P1-2, polarizers; BS, beam splitter; PBS, polarizing beam splitter; L1-6, lenses; M1-3, mirrors; SP, spectrometer; PC, polarization controller; SMF, single mode fiber; DOP, degree of polarization; DGD, differential group delay.

added the fringes from two spectrometers, $F_{\text{nops}}(k) = F_x(k) + F_y(k)$. The fading coefficient P was measured as the ratio between the peak amplitude of $\mathcal{F}[F_{\text{nops}}(k)]$ and the summation of peak amplitudes of $\mathcal{F}[F_x(k)]$, $\mathcal{F}[F_y(k)]$, where $\mathcal{F}[\cdot]$ is the Fourier transformation.

We recorded 200 fringes with randomly different positions of the PC paddles. Figure 2(b) is the measured fading coefficient P against the value of $\cos(A/2)$, where A is the misalignment angle between vectors $\mathbf{s}_{\text{ref}}$ and $\mathbf{s}_{\text{mirror}}$ on the Poincare sphere. Though the overall measured points were regressing well to the theoretical linear relation [red line in Fig. 2(b)], it was noticed that disagreement existed in some individual points. One reason for this deviation may be the PMD effect of the fiber, which means the $\mathbf{s}_{\text{mirror}}$ were varying at different wavelengths. Thus, the fading coefficient P was varying along the k -space. We used the DOP to characterize the PMD effect over the entire spectrum. In the Stokes representation, the DOP is defined as $\text{DOP} = \sum_k [s_1(k) + s_2(k) + s_3(k)] / \sum_k s_0(k)$. From the DOP color-encoded measurement points [Fig. 2(b)], a lower DOP resulted in larger deviation. In Fig. 2(c), we counted the distribution of DOP of the 200 measurements. The measured DOP was high (close to 1) in most cases. Therefore, it is acceptable to ignore the PMD effect in the theoretical analysis and numerical simulation. To further quantify the PMD effect and the birefringence of the round-trip sample arm fiber, we modeled this fiber as a pure retarder [11] and reconstructed the Jones matrix $\mathbf{J}_{\text{sam}}$ of a particular wavelength (860 nm in this calculation). By $\text{DGD} = 2\sqrt{\det(d(\mathbf{J}_{\text{sam}})/d\lambda)}$ (where $\det$ is the determinant of a matrix), we measured the differential group delay (DGD) and plotted its distribution in Fig. 2(d). The mean DGD was measured to be 9.9 fs, and the distribution was a good fit (p value = 0.46 with χ^2 test) to a Rayleigh distribution, which is the theoretical probability density function (PDF) of DGD [11]. The PMD measurement is necessary to confirm that the birefringence of 1.5 m fiber was large enough to fully randomize the output light polarization state. In addition, as previously reported [8], the PMD effect results in a variation of the fading coefficient P in k -space, inducing amplitude and phase modulations on the fringe, which degrades the axial point spread function.

As reported in the literature [7,11,12], an interesting observation was that the output polarization states of the round-trip light from a SMF cable were not evenly distributed on the Poincare sphere, which can be observed in Fig. 3(a), where the k -space-average polarization states of the 200 measured fringes were plotted on the Poincare sphere. We can see that the polarization states tended to concentrate to the point $[-0.54 \ -0.23 \ -0.8]^T$. To further study this observation, we numerically simulated the process of monochromatic light traveling a round-trip in a piece of SMF fiber. The fiber was modeled using a randomly generated Jones matrix following [13]. Based on 5000 runs of simulation, two statements were concluded. (1) For round-trip SMF with an arbitrary input polarization state, $[s_1 \ s_2 \ s_3]^T$ in Stokes representation, the highest probability output polarization state will be $[s_1 \ s_2 \ -s_3]^T$ and, in contrast, the lowest probability point will be $[-s_1 \ -s_2 \ s_3]^T$. (2) The probability of the output polarization state would be mono-decreasing with its angle to $[s_1 \ s_2 \ -s_3]^T$ on the Poincare sphere.

Based on the above observation and Eq. (3), there exists an optimal output reference polarization state maximizing the

Fig. 3. (a) Normalized polarization states distributed on the Poincare sphere of a piece of round-trip SMF. The input polarization state was $\mathbf{s}_{\text{input}}$. Most output polarization states were distributed close to $\mathbf{s}_{\text{ORPS}}$. (b)–(d) Empirical PDFs based on a numerical simulation and corresponding measured histograms of the fading coefficient P , respectively, when $A_{\text{ref}} = 0^\circ$, 90° , and 180° . A_{ref} is the angle between the reference output $\mathbf{s}_{\text{ref}}$ and $\mathbf{s}_{\text{ORPS}}$.

average SNR of the fringes. We noted the optimal reference polarization state as $\mathbf{s}_{\text{ORPS}}$ (Stokes vector of optimal reference polarization state). Based on our analysis, $\mathbf{s}_{\text{ORPS}}$ should be equal to $[s_1 \ s_2 \ -s_3]^T$, given that $[s_1 \ s_2 \ s_3]^T$ is the input state. We took three cases to illuminate and evaluate this optimization. For each case, the angle between $\mathbf{s}_{\text{ref}}$ and $\mathbf{s}_{\text{ORPS}}$ on the Poincare sphere, noted as A_{ref} , was 0° , 90° , and 180° , respectively. We estimated the PDF of the fading coefficient P in each case using the kernel density estimation method. Based on the 5000 runs of numerical simulation, without regard to the PMD effect, using the “box” kernel, the empirical PDFs of P in each case were plotted in Figs. 3(b)–3(d) with green lines, with the mean and variance labeled by their sides. In the optimal case [Fig. 3(b)], the average SNR is 3.97 dB higher than the worst case [Fig. 3(d)].

To verify the results of the numerical simulation, we used the previously measured 200 Stokes vectors to test the empirical PDFs. In our setup, the sample arm input polarization state was expected to be right circular polarized, which fell at $+V$ point on the Poincare sphere. Therefore, the optimum reference output polarization state should be left circular polarized, at $-V$ point on the Poincare sphere. Due to an imperfection of the optical components and optics alignment, there obviously existed an error. The $\mathbf{s}_{\text{ORPS}}$ was measured to be $[-0.54 \ -0.23 \ -0.8]^T$. To match the three simulation cases, we calculated the angles between the measured Stokes vectors and the three polarization states of $[-0.54 \ -0.23 \ -0.8]^T$ ($A_{\text{ref}} = 0^\circ$), $[0.58 \ 0.58 \ -0.56]^T$ ($A_{\text{ref}} = 90^\circ$), and $[0.54 \ 0.23 \ 0.8]^T$ ($A_{\text{ref}} = 180^\circ$). We plotted the histograms together with respect to empirical PDFs, shown in Figs. 3(b)–3(d).

However, not all light sources are fully polarized. An extreme example is supercontinuum sources, which inherently generate light by a random process, thereby producing unpolarized light. Other cases such as superluminescent diodes (SLDs) produce substantially polarized light. Meanwhile, many light source manipulations would depolarize the light, such as the light combination of an SLD array, or simply passing the light through a long piece of SMF.

Fully unpolarized light source can be modeled as a combination of two cross-polarized beams without statistical correlation between each other [14]. We assume that $\mathbf{j}_{\text{ref}}$ and $\mathbf{j}_{\text{mirror}}$ are the corresponding arbitrary Jones vectors if the source is switched to fully polarized, given that the cross-polarization state of a Jones vector $\mathbf{j}$ is $(\text{anti-diag}\{-1, 1\}) \cdot \mathbf{j}^*$, where

anti-diag $\{\cdot\}$ is an anti-diagonal matrix. Superscript * is the conjugate operator. Therefore, for OCT using unpolarized light, Eq. (1) can be re-written as

$$\begin{aligned} f_{\text{upo}}(k) &= \frac{\mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{sam}}}{2} + \frac{\left(\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \mathbf{j}_{\text{ref}}^* \right)^\dagger \left(\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \mathbf{j}_{\text{sam}}^* \right)}{2} \\ &= \frac{\mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{sam}}}{2} + \frac{\mathbf{j}_{\text{sam}}^\dagger \mathbf{j}_{\text{ref}}}{2} \\ &= \Re[\mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{mirror}}] F(k), \end{aligned} \quad (4)$$

where $\Re[\cdot]$ is the real part. $f_{\text{upo}}(k)$ is the detected complex fringes after background subtraction. We cannot find a concise representation for the fading coefficient P_{upo} in Stokes. From $P_{\text{upo}} = \Re[\mathbf{j}_{\text{ref}}^\dagger \mathbf{j}_{\text{mirror}}]$, we can see that the probability distribution of P_{upo} is also affected by the $\mathbf{j}_{\text{ref}}$, meaning that we can change the distribution of P_{upo} by changing the reference SMF. However, there is no obvious configuration to maximize P_{upo} . Specifically, no matter how we configure $\mathbf{j}_{\text{ref}}$, the distribution of P_{upo} is always nearly central-symmetric with a mean around 0.5.

We built up a beam splitter-based single-spectrometer OCT system to demonstrate the proposed optimal polarization management. Shown in Fig. 4(a), the light source was a supercontinuum source centered at 800 nm. A free-space beam splitter was used for convenient management of the polarization states. Two polarizers were inserted into the input port (P1) and the reference port (P2). Based on our analysis, if the input polarization state $\mathbf{s}_{\text{in}}$ is linearly polarized, the optimal reference output polarization state $\mathbf{s}_{\text{ORPS}}$ should be equal to $\mathbf{s}_{\text{in}}$. Thus, the optimization can be achieved by aligning the optic axes of the two polarizers, P1 and P2, forcing $\mathbf{s}_{\text{ref}} = \mathbf{s}_{\text{in}} = \mathbf{s}_{\text{ORPS}}$.

Fig. 4. (a) Beam splitter-based single-spectrometer OCT setup. (b) Measured fading coefficient histograms with optimal and sub-optimal reference output polarization states and an unpolarized light source. PC, polarization controller; L1-4, lenses; P1-2, polarizers.

We recorded 1024 fringes, while randomly changing the PC in the sample arm. To make a comparison, we also recorded fringes under two other configurations. One was a sub-optimal configuration where the angle of the two polarizers were around 45° , corresponding to $A_{\text{ref}} = 90^\circ$; the other used an unpolarized source achieved by removing the two polarizers (P1 and P2). In all of these recordings, the light intensity illuminated on the detectors from the sample and reference arms was adjusted to be identical. The measured normalized fading coefficients are shown in the histograms in Fig. 4(b). Conforming with our prediction, aligning $\mathbf{s}_{\text{ref}}$ to $\mathbf{s}_{\text{ORPS}}$ resulted in the highest average SNR, and the optimal average amplitude was 1.5 times higher than an unpolarized source OCT without any polarization management, corresponding to a 3.5 dB sensitivity improvement.

In this Letter, we quantified the polarization randomization-induced SNR loss in fiber-based OCT and proposed a polarization management method to mitigate the SNR loss. Based on our analysis, we suggested the development of broadband fiber couplers integrating two inline polarizers, one at the input tail and one at the output tail, for the construction of a robust, high-SNR, low-cost, and flexible OCT system.

Funding. National Research Foundation Singapore (NRF) (NRF-CRP13-2014-05); National Medical Research Council (NMRC) (NMRC/CBRG/0036/2013); Ministry of Education-Singapore (MOE) (MOE2013-T2-2-107); NTU-AIT-MUV program in Advanced Biomedical Imaging (NAM/15005).

Acknowledgment. The authors acknowledge the valuable suggestions and proofreading of the manuscript from Dr. Martin Villiger of Massachusetts General Hospital (Boston, USA). They also acknowledge the help in empirical distribution estimation from Ms. Chen Zhang from the National University of Singapore (Singapore).

[†]These authors contributed equally to this Letter.

REFERENCES

- M. J. Gora, M. J. Suter, G. J. Tearney, and X. Li, *Biomed. Opt. Express* **8**, 2405 (2017).
- J. Gordon and H. Kogelnik, *Proc. Natl. Acad. Sci. USA* **97**, 4541 (2000).
- M. C. Pierce, M. Shishkov, B. H. Park, N. A. Nassif, B. E. Bouma, G. J. Tearney, and J. F. de Boer, *Opt. Express* **13**, 5739 (2005).
- A. M. Lee, H. Pahlevaninezhad, V. X. Yang, S. Lam, C. MacAulay, and P. Lane, *Opt. Lett.* **39**, 3638 (2014).
- G. Tearney, E. Swanson, J. Fujimoto, B. Bouma, S. Boppart, and B. Golubovic, *Opt. Lett.* **21**, 1408 (1996).
- D. Cui, K. K. Chu, B. Yin, T. N. Ford, C. Hyun, H. M. Leung, J. A. Gardecki, G. M. Solomon, S. E. Birket, L. Liu, S. M. Rowe, and G. J. Tearney, *Opt. Lett.* **42**, 867 (2017).
- M. O. Van Deventer, *J. Lightwave Technol.* **11**, 1895 (1993).
- S. Jiao and M. Ruggeri, *J. Biomed. Opt.* **13**, 060503 (2008).
- M. Villiger, E. Z. Zhang, S. Nadkarni, W.-Y. Oh, B. E. Bouma, and B. J. Vakoc, *Opt. Lett.* **38**, 923 (2013).
- E. Z. Zhang, W.-Y. Oh, M. L. Villiger, L. Chen, B. E. Bouma, and B. J. Vakoc, *Opt. Express* **21**, 1163 (2013).
- F. Corsi, A. Galtarossa, and L. Palmieri, *J. Lightwave Technol.* **16**, 1832 (1998).
- E. Brinkmeyer, *Opt. Lett.* **6**, 575 (1981).
- A. Dal Forno, A. Paradisi, R. Passy, and J. Von der Weid, *IEEE Photon. Technol. Lett.* **12**, 296 (2000).
- K. H. Kim, B. H. Park, Y. Tu, T. Hasan, B. Lee, J. Li, and J. F. de Boer, *Opt. Express* **19**, 552 (2011).