Ultra-high-resolution SD-OCM imaging with a compact polarization-aligned 840 nm broadband combined-SLED source

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Abstract: We analyze the influence of intrinsic polarization alignment on image quality and axial resolution employing a broadband 840 nm light source with an optical bandwidth of 160 nm and an output power of 12 mW tailored for spectral-domain optical coherence microscopy (SD-OCM) applications. Three superluminescent diodes (SLEDs) are integrated into a 14-pin butterfly module using a free-space micro-optical bench architecture, maintaining a constant polarization state across the full spectral output. We demonstrate superior imaging performance in comparison to traditionally coupled-SLED broadband light sources in a teleost model organism in-vivo.

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1. Introduction

Since the early 1990s, optical coherence tomography (OCT) [1] became an established and important optical imaging modality, revolutionizing the field of ophthalmology [2], and aiding research and diagnosis in the fields of cardiology [3] and dermatology [4]. Along with the introduction of time-domain OCT came considerable technological advancements in the area of broadband low coherent light source technology to enhance the axial resolution of OCT, enabling ultrahigh-resolution imaging in pre-clinical and clinical settings [5–7].

Sensitivity and acquisition speed were considerably improved with the transition from time-domain to Fourier-domain (FD-)OCT [8–10]. At the same time, the use of superluminescent diodes (SLED), swept-wavelength laser sources (SS) and Fourier-domain mode-locked (FDML) lasers became more popular to satisfy the increasing demand for high-speed imaging in order to reduce motion artifacts [11–14]. While imaging speed is particularly important in the fields of ophthalmology, cardiology and dermatology, spectral bandwidth became particularly important for ultra-high-resolution OCT microscopy.

Near-infrared OCT microscopy provides an interesting and promising alternative to classical imaging methods such as fluorescence and laser scanning microscopy. The technology allows intrinsic 3-D reconstructions of cells and bigger samples with fields of view of several millimeters without sectioning. The method usually operates in the near-infrared wavelength region between 800 nm and 1300 nm. The shorter wavelength region provides better axial resolution and increased contrast for a fixed bandwidth, while longer wavelengths are preferred to image below the surface in highly scattering tissue [15].

Raster scanning optical coherence microscopy (OCM) usually employs broad-bandwidth SLEDs, supercontinuum-, or mode-locked femtosecond solid state lasers as light sources [16].
Femtosecond lasers offer superior performance in terms of bandwidth and output power [17], but they are complex to build and operate and are typically expensive. Compared to SLEDs, femtosecond and supercontinuum light sources suffer from higher random intensity and phase noise [18,19]. SLEDs are less expensive, compact and easy to operate and are, therefore, often the light source of choice, particularly for ultra-high-resolution spectral-domain (SD-)OCM with a center wavelength around 840 nm.

SLEDs have typical bandwidths of 40 nm to 80 nm and ex-fiber output powers up to 20 mW [16]. To achieve axial resolutions of approximately 3 µm in air, multiple fiber-pigtailed SLED modules need to be spectrally combined using fused-fiber couplers or fiberized wavelength division multiplexer couplers. However, fiber coupling has the drawback, that polarization states of individual SLEDs are not intrinsically aligned.

In this work, we analyze the influence of intrinsic polarization alignment on image quality and axial resolution in the presence of birefringent material and tissue. Therefore, a novel, integrated, combined-SLED light source (EBD290002, EXALOS) is tested against a state-of-the-art combined SLED broadband light source with similar spectral bandwidth and output power (EBS300080, EXALOS) for OCM applications. Both broadband light sources have a comparable 10 dB bandwidth of around 160 nm, similar 3 dB bandwidths of 133 nm (EBD29) and 144 nm (EBS30) as well as similar output powers of 12 mW (EBD29) and 11 mW (EBS30). For the EBD29 three SLED chips are integrated in a compact 14-pin butterfly package with a thermo-electric cooler for temperature stabilization. The individual light output of the three SLED chips is collimated using micro-optical lenses and then spatially and spectrally combined using dichroic wavelength filters before being coupled into a HI-780 single-mode output fiber. Besides a considerable reduction in size, such an approach offers the advantage of intrinsic polarization alignment. The combined spectrum has the same linear horizontal polarization across all wavelengths with an average polarization extinction ratio (PER) of 20 dB.

2. Methods

The ultra-high-resolution SD-OCM system is based on a standard bulk-optics Michelson interferometer with a 90:10 beamsplitter (Fig. 1(a)). Its spectrometer comprises a transmitting diffraction grating (3253-W-01, Wasatch Photonics), a lens system (85 mm f/2.0 Makro-Planar T, Zeiss) and a line scan camera (Sprint spl4096-140km, Basler), where 2500 pixel are used for imaging. Thus, the spectrometer has a spectral resolution of 0.063 nm and a 2.84 mm theoretical imaging depth in air [20] (calculated using the 10 dB bandwidth of the EBD29). The sample arm uses a pair of galvanometer scanners (CTI6220H, Cambridge Technology), a 4 focal length lens (4-f) telescope (AC254-050-B-ML and AC254-075-B, Thorlabs) and a telecentric microscope objective (UPlanSApo 4, Olympus) to perform raster scanning across the sample. The full width at half maximum beam diameter is 8 mm after the collimator (RC08APC-P01, Thorlabs). To fill the aperture of the microscope objective (NA = 0.16) the beam is expanded to 12 mm with the 4-f telescope. To minimize dispersion, all optical elements are also integrated into the reference arm. Standard OCT data processing (re-scaling, zero padding, dispersion compensation, fast Fourier transform) is performed on the acquired interferograms [21].

For OCM performance evaluation, the two light sources (EBD29 and EBS30) are fiber-coupled into the bulk optics OCM system with the ex-fiber output power of both light sources set to 8 mW. The complete system specifications are summarized in Table 1. Measurements of the amplified spontaneous emission (ASE) output spectra for the EBD29 and EBS30, provided by the manufacturer, are shown in Fig. 2(a) and 2(b). The ASE spectra are acquired with an optical spectrum analyzer (AQ6370C, YOKOGAWA) over a wide spectral range in order to provide fine spatial resolution. The optical spectrum analyzer is operated at the highest optical resolution of 20 pm with a large degree of numerical oversampling. The acquired optical spectra are re-sampled to provide equidistant sampling points in k-space in order to calculate the corresponding linear
coherence functions by using a Fourier transformation without additional windowing or digital filtering (Fig. 2(c) and 2(d)).

![Fig. 1.](image1.png)  
**Fig. 1.** Ultra-high-resolution SD-OCM system. (a) System sketch. (b) 14-pin butterfly combi-SLED module (yellow ellipse) on OEM driver board EBD9200. (c) Open combi-SLED module with 3 SLEDs ($D_1$, $D_2$, $D_3$); DM: Dichroic mirror; $L_1$ to $L_3$: Collimation lenses; F: Optical fiber; L: Focusing lens; PD: Monitoring photodiode; Green, yellow and magenta dotted arrows: Optical beam path for the individual diodes $D_1$, $D_2$ and $D_3$ respectively; Red dotted arrow: Common optical beam path.

![Fig. 2.](image2.png)  
**Fig. 2.** ASE spectrum and calculated coherence function. (a, b): Linear ASE spectrum of the EBD29 and EBS30. (c, d): calculated linear coherence function of the EBD29 and EBS30. The corresponding bandwidths and calculated axial resolutions can be found in Table 1.
Table 1. OCM specifications for the combi-SLED (EBD29) and classical three SLED light source (EBS30).

| Light source | EBD29 | EBS30 | Light source | EBD29 | EBS30 |
|--------------|-------|-------|--------------|-------|-------|
| Center wavelength | 847 nm | 844 nm | Sensitivity | 97 dB | 96 dB |
| Bandwidth (10 dB) | 158 nm | 161 nm | Coherence length (air) | 3.1 µm | 2.9 µm |
| Output power | 12.1 mW | 10.9 mW | Transverse resolution | 2.4 µm | 2.4 µm |
| Power on sample | 500 µW | 500 µW | Depth of focus [22] | 74 µm | 74 µm |

2.1. "EBD29 - optical light source architecture"

The optical module is realized as a standard 14-pin butterfly package (20.8 mm · 12.7 mm) with a ceramic plate acting as optical bench that is soldered onto a thermoelectric cooler (Fig. 1(c)). Three SLED chips (D₁ to D₃) are mounted on individual ceramic submounts, which are soldered onto the optical bench. The three SLED modules have center wavelengths of 885 nm, 840 nm and 798 nm with 3 dB bandwidth values of 63 nm, 49 nm and 40 nm, respectively. Micro-optical lenses (L₁ to L₃, 1 mm · 1 mm) are used to collimate the light output of every SLED chip. Dielectric mirrors (DM) are employed to align and spectrally combine the three individual collimated output beams. The combined beam is focused into a HI-780 single-mode fiber (F) using a micro-optical focusing lens. Additionally, a photodiode (PD) monitors the ex-fiber optical output power of the module and a negative temperature coefficient thermistor is used for temperature stabilization of the optical bench. All optical components are assembled and aligned with sub-micron precision by an automated assembly robot using dual-curable (UV light and thermal baking) epoxy glues for fixation [23–25]. The combi-SLED module is mounted on a 3-channel OEM driver board (EBD9200), providing ultra-stable current operation and temperature control (Fig. 1(b)).

Each SLED chip can be operated individually since the 14-pin butterfly module features separate anode and cathode pins for each SLED. The coupling efficiency from the SLED chips to the fiber is roughly 25%, including free-space propagation and filtering losses at the dichroic beam combining filters, resulting in a total output power of 12.1 mW for this prototype.

2.2. "EBS30 - optical light source architecture"

The benchtop broadband light source is realized with a standard architecture comprising three individual SLED devices. Each SLED is realized as a fiber-pigtailed 14-pin butterfly module that is operated on an individual OEM driver board (EBD5200). The three SLED modules have center wavelengths of 880 nm, 840 nm and 785 nm with 3 dB bandwidth values of 65 nm, 50 nm and 20 nm, respectively. The optical output of each module has a power level of around 5 mW and is spectrally combined with fused fiber couplers or fiberized wavelength-division multiplexing (WDM) filters. Because of the limited bandwidth of the 785 nm SLED, the combined spectrum has a significant dip of around 13 dB at approximately 810 nm, as shown in Fig. 2(b). Despite the strong spectral dip, the sidelobes of the coherence functions are reasonably well suppressed, as shown in Fig. 2(d). This spectral dip could be eliminated using the same broadband SLED at 800 nm, which was also used for the EBD29 light source. As mentioned earlier, the 14-pin butterfly modules are not realized with polarization-maintaining (PM) fibers, hence the polarization states are not maintained and not well aligned across the combined optical spectrum. Other performance parameters are listed in Table 1.

3. Results

For careful analysis of the effect of polarization alignment on the OCT image quality, we organized the results section into two subsections. We first analyze the general effect of polarization changes
3.1. Impact of source polarization on the OCM PSF

A commercial spectrometer (AVS-USB2000, Avantes) is placed at the output of the first collimator to evaluate spectral intensity variations caused by varying polarization states induced by the polarization controller shown in Fig. 1(a). Figure 3(a) and Fig. 3(b) show variations in the recorded spectral intensity for the EBD29 and EBS30, respectively. The variations occur due to the spectrometer’s intrinsic polarization dependent efficiency of the charged coupled device detector and its integrated optical components.

Fig. 3. Polarization dependent spectral intensity variations of the EBD29 and EBS30 SLEDs measured with a commercial spectrometer (AVS-USB2000, Avantes). (a, b) Spectral intensity for the EBD29 and EBS30. Polarization state 1: magenta; Polarization state 2: blue; Polarization state 3: green. (c, d) Ratio between polarization state 1 and 3 (magenta), 1 and 2 (blue), 2 and 3 (green) for the EBD29 and EBS30.

Three polarization states are chosen to represent maximum (magenta), medium (blue) and minimum (green) detected spectral intensity for the EBD29. Depending on the polarization state, the EBD29 shows a uniform decrease in intensity over the whole spectral range. The behavior is demonstrated in the plot illustrating the ratios between maximum and minimum (magenta), maximum and medium (blue) and medium to minimum (green) intensities (Fig. 3(c)). As expected, the behavior for all three ratios is similar, while the intensity ratio changes in absolute value due to the selected ratios. The EBS30 shows a different behavior. The detected spectral intensity is not uniformly decreasing for the three SLEDs (Fig. 3(b)). Polarization dependent jumps in signal ratios are clearly illustrated in Fig. 3(d).

A mirror is placed in the OCM sample arm and the coherence function is evaluated after standard OCM processing (Fig. 4). The manual polarization controllers are used to set input polarization states 1 and 2 (magenta and blue). The EBD29 shows no polarization dependent behavior (Fig. 4(a)). Due to the polarization state mismatch of the three SLEDs and the polarization dependent transmission and detection efficiencies of the OCM system and spectrometer, the side lobe symmetry changes for the EBS30 (Fig. 4(b)). The measured OCM axial resolution is 3.3 µm for the EBD29 and 3.1 µm for the EBS30 (full width at half maximum).

To simulate tissue birefringent effects, a quarter-wave plate is added to the sample arm. Depending on the wave plates fast-axis position, the initial linear horizontal polarization

on the measured spectrum and the axial OCT point-spread-function (PSF). Subsequently, we analyze the impact of spectral polarization changes of the source on the \textit{in-vivo} OCM imaging performance.
Fig. 4. Input polarization dependent OCM coherence function. The coherence functions are acquired at 500 µm distance to the zero delay. (a, b) Coherence function of the EBD29 and EBS30. Magenta: input polarization 1; blue: input polarization 2.

(measured with a PAX5710IR1-T TXP polarimeter, Thorlabs) is altered (Fig. 5(a)). At a 45° fast-axis angle (Fig. 5(b), magenta), the horizontally polarized light becomes circularly polarized. After the mirror, the chirality of the circularly polarized light changes. Eventually, after passing the quarter-wave plate a second time, the light will be vertically polarized. This case should minimize interference between sample (vertically polarized light) and reference arm (horizontally polarized light).

Fig. 5. Interference pattern and coherence function for the EBD29 and EBS30 light sources for different quarter-wave plate orientations. (a) Graphical illustration for horizontally polarized light (H) traversing a quarter-wave plate (λ/4, 45° fast-axis orientation) a second time after being reflected by a mirror. V: vertically polarized light; Circular arrow: chirality of circularly polarized light. (b) Color coding for various fast-axis orientations of the quarter-wave plate. (c, d) Interference pattern produced by the EBD29 and EBS30 light source for three quarter-wave plate orientations. (e, f) Coherence functions produced by the EBD29 and EBS30 light source for three quarter-wave plate orientations. The coherence functions are acquired at 500 µm distance to the zero delay.
polarized light). The polarization states of the light beams should remain unaltered for a $0^\circ$ and $90^\circ$ fast-axis orientation of the quarter-wave plate (Fig. 5(b), blue and green curves).

Figure 5(c) and 5(d) illustrate the interference pattern acquired with the OCM spectrometer for both light sources. The EBD29 interference pattern, due to aligned polarization states across the entire spectrum, behaves as expected. Maximum interference occurs at quarter-wave plate fast-axis positions $0^\circ$ and $90^\circ$ (blue and green), while a $45^\circ$ orientation minimizes interference (magenta). The interference pattern of the EBS30 behaves differently. Depending on the initial polarization state of each SLED, the interference will be at maximum, minimum or in-between, but certainly different, for all quarter-wave plate orientations.

The mismatch of polarization states among the three SLEDs in the EBS30 source leads to a substantial decrease in axial resolution for most quarter-wave plate positions (Fig. 5(f)). Due to the intrinsic polarization alignment, the axial resolution is preserved using the EBD29 light source (Fig. 5(e)). The signal amplitude depends on the quarter-wave plate position for both light sources.

3.2. Source polarization impact on OCM imaging

The OCM imaging performance of both light sources is compared in an *in-vivo* imaging situation. In order to study the impact of polarization, a ten times averaged B-scan of a zebrafish larva (72 hours post fertilization) is acquired with two distinct incident polarization states (Fig. 6).

![Fig. 6. Averaged (10x) intensity B-scans of a zebrafish larva acquired for two polarization states with two light sources. Fiber polarization controller position 1 corresponds to a horizontal linear and position 2 to a circular polarization state. The polarization states are measured for the EBD29 light source with a PAX5710IR1-T TXP polarimeter. (a, b) Polarization state 1 and 2 acquired with the EBD29 light source. (c, d) Polarization state 1 and 2 acquired with the EBS30 light source. Blue marks: regions of interest; Yellow arrows: artifacts caused by PSF side lobes; Magenta arrows: polarization dependent PSF side lobe amplitudes; Green arrows: same speckle in all images; Green star: highest visibility for polarization state dependent signal amplitudes; Magenta triangles: caudal vein (left) and dorsal aorta (right); YS: yolk sack; MT: myotomes (large muscle segments); NC: notochord; SC: spinal cord]
The fish is embedded in phytalgel after anesthesia and rests in a recovery position [26]. The B-scan is taken at approximately one third of the body length, measured from the head of the fish (approx. 1.3 mm). Polarization state dependent signal amplitudes can be identified at various locations throughout the B-scan and are particularly well visible at the location of the green star. The effect is more pronounced in deeper regions (bottom of the image) of the fish, suggesting the impact of polarization mode dispersion (PMD), while the OCM beam penetrates deeper into the fish. For the EBS30 generated images, the axial resolution is found to be visibly degraded at the positions surrounded with blue markings. Internal structures are visible at the lower part of the yolk sack (YS) for the EBD29 light source (Fig. 6(a) and 6(b), region 1). Those structures cannot be identified for the EBS30 at the same B-scan position (Fig. 6(c) and 6(d), region 1). The same behavior can be observed along the lower zebrafish/phytalgel interface (regions 2-4). The green arrow points to the same speckle for all four images. In this case a change in axial resolution due to polarization state changes can be directly observed for the EBS30 light source images but not for the EBD29 light source images. Polarization dependent axial resolution changes can also be observed at the position of the dorsal fin fold (region 4) of the EBS30 light source images. Artifacts caused by PSF side lobes (yellow arrows) appear in all intensity images (Fig. 6(a)-d), but are weaker for the EBD29 light source, due to its spectral power distribution. Polarization dependent side lobe amplitudes can be identified for the EBS30 light source (magenta arrows).

4. Discussion

Ultra-high-resolution SD-OCM can be achieved with a variety of light sources, for example Titanium:sapphire (Ti:Sapph) lasers [17,27] or supercontinuum sources [28], offering large bandwidths and high output powers. On the other hand, those light sources are costly, mostly bulky and have a higher relative intensity noise, thus provide lower SNR compared to SLEDs [18,19].

Single SLEDs provide a much smaller wavelength bandwidth than Ti:Sapph or supercontinuum based light sources. Therefore, several SLEDs of different center wavelengths, usually two to four, are coupled together to provide a larger bandwidth to enable ultra-high-resolution SD-OCM with an axial resolution of approximately 3 µm in air.

SLEDs for OCM and optical coherence tomography (OCT) in the near-infrared wavelength range are, for example, manufactured by Superlum Diodes Ltd. and EXALOS AG. Both companies offer benchtop solutions (EBS- and M-T- series, Table 2) or driver board solutions (EBD- and BLM- series, Table 2) with comparable specifications. Benchtop solutions are bulky and heavy (3000 g to 4000 g), but they are easy and comfortable to use. Driver board solutions require additional electronics, but they are lightweight and compact. Both companies provide various bandwidth models, but Superlum Diodes Ltd. usually provides higher output power.

Table 2. Comparison of currently available broadband OCM and OCT SLED light sources. EBS- and M-T- sources are benchtop solutions. The BLM2-D-840-B-10 is a two SLED driver board light source, which is compact and light weight, but offers considerably lower bandwidth and lower output power than the SLED driver board solutions (EBD290002-00 and cBLMD-T-850-HP). Green: optimal specifications for OCM; Blue: polarization matched output; Yellow: average specifications for OCM; Magenta: bulky or low-end specifications for OCM.

|                      | EXALOS AG | Superlum Diodes Ltd |
|----------------------|-----------|---------------------|
| **Center Wavelength**| 845 nm    | 845 nm              |
| 3dB Bandwidth        | 160 nm    | 140 nm              |
| Coherence Length     | 2.9 µm    | 3.4 µm              |
| Output Power         | 9 mW      | 9 mW                |
| SLED coupling        | Fiber couplers | Fiber couplers |
| Dimensions (W x D x H)| 180 x 260 x 129 mm | 88 x 120 x 29 mm |
| Weight               | 3000 g    | 465 g               |
| 850 nm               | 850 nm    | 840 nm              |
| 160 nm               | 155 nm    | 90 nm               |
| 3.9 µm               | 3.1 µm    | 5.2 µm              |
| 12 mW                | 12 mW     | 10 mW               |
| Fiber couplers       | Fiber couplers | Fiber couplers |
| 251 x 112 x 192 mm  | 190 x 110 x 31 mm |
| 4000 g              | 950 g     | 400 g               |

In addition, all broadband fiber couplers would have to support PM fibers as well, which is demanding and expensive. The use of a polarizer will also eliminate artifacts due to polarization alignment effects, but that is also not common practice. Myotomes in zebrafish larvae are highly organized muscle segments, their behavior and resulting degradation of the axial resolution of fiber-couple sources in the presence of birefringent material. It has been demonstrated that a misalignment of SLED polarization states are causing a severe degradation of the axial resolution in fiber-based OCT systems [29]. In this work we demonstrate that also OCM and OCT systems based on bulk optics suffer from a significant degradation of optical coherence tomography (PS-OCT) [33]. Several methods have been developed to correct or mitigate the impact of PMD to the Jones matrix measured by PS-OCT [34–38]. It may be possible to correct the point spread function, distorted by the PMD of the SLED light source, by combining the output of several SLEDs. The quarter-wave plate used to generate the graphs in Fig. 6 is set to the optimal polarization state of the EBD29 light source images. Polarization dependent axial resolution changes can also be observed at the position of the dorsal fin fold (region 4) of the EBS30 light source images. Artifacts caused by PSF side lobes (yellow arrows) appear in all intensity images (Fig. 6(a)-d), but are weaker for the EBD29 light source, due to its spectral power distribution. Polarization dependent side lobe amplitudes can be identified for the EBS30 light source (magenta arrows).
In this work we tested a novel light source, the EBD290002-00 (Table 2), where three SLED chips are integrated in a compact 14-pin butterfly package. Unlike traditional SLED chip coupling with fiber couplers, the individual light output of the three SLED chips is collimated using micro-optical lenses and is then spatially and spectrally combined using dichroic wavelength filters before being coupled into a HI-780 singlemode output fiber. Such an approach leads to a considerable reduction of the light source’s size and weight (Table 2). A potential drawback of such a design is the lost flexibility to fine-tune the spectral shape of each SLED by modifying the temperature. Therefore, the optimum spectral shape is adjusted during the build process of the combined-SLED module. The operating current is tuned for each SLED individually, thereby giving a certain spectral shape, and then the shape of the combined spectrum is optimized using the free-space optical components, for example the dichroic filters.

The free-space combination of SLED light in the EBD29 is a novelty and offers the advantage of intrinsic polarization alignment. The combined spectrum has the same linear horizontal polarization across all wavelengths. Currently, SLED coupling is performed with fiber optic couplers for all light sources (except the EBD29). Since fibers are used for coupling, the polarization states of the individual SLEDs are different. Theoretically, it would be possible to achieve aligned polarization states in classical SLED sources by using polarization controllers on each fiber link between an SLED module and a fiber coupler, or also in between fiber couplers. If e.g. three SLEDs are spectrally multiplexed, a total of four polarization controllers would be needed. In addition, such mechanical alignment is never truly stable during transportation or over a wider temperature range. Another option would be to package each individual SLED chip in a module with polarization-maintaining (PM) fibers, but that is also not common practice. In addition, all broadband fiber couplers would have to support PM fibers as well, which is demanding and expensive.

It has been demonstrated that a misalignment of SLED polarization states are causing a severe degradation of the axial resolution in fiber based OCM systems [29]. In this work we demonstrate that also OCM and OCT systems based on bulk optics suffer from a significant degradation of the axial resolution in the presence of birefringent material and tissue if fiber couplers are used to combine the output of several SLEDs. The quarter-wave plate used to generate the graphs in Fig. 5 simulates the presence of birefringent tissue. Figures 5(d) and 5(f) illustrate the interferometric behavior and resulting degradation of the axial resolution of fiber-coupled sources in the presence of birefringent material. Myotomes in zebrafish larvae are highly organized muscle segments, which also introduce birefringence to the sample arm [30]. Figure 6 illustrates improved image quality with the EBD29 light source, due to matched SLED polarization states.

We expect even stronger effects for retinal imaging in the human or animal eye with broadband light sources using SD-OCT due to retinal nerve fiber and cornea birefringence [31,32]. It is known that a small amount of PMD also causes artifacts in polarization-sensitive optical coherence tomography (PS-OCT) [33]. Several methods have been developed to correct or mitigate the impact of PMD to the Jones matrix measured by PS-OCT [34–38]. It may be possible to correct the point spread function, distorted by the PMD of the SLED light source as well as those methods of PS-OCT, with a careful modification of the algorithms by utilizing a polarization-sensitive interferometer. However, such approach requires a PS-OCT setup and further development of numerical processing algorithms.

The use of a polarizer will also eliminate artifacts due to polarization alignment effects, but will reduce the overall output power of the light source. Additionally, the spectral intensity will be reduced differently for different SLEDs as indicated by the loss in signal intensity, particularly for the third SLED in Fig. 3(b) by switching from the magenta to the blue polarization state. The mentioned problems can eventually be avoided by using a SLED light source which uses free-space spectral coupling of SLEDs.
5. Conclusion

We demonstrated axial resolution degradation in the presence of birefringent material and tissue for OCM and OCT systems based on bulk optics with sources that exhibit spectrally dependent polarization. This is challenging for fiber-coupled multi-SLED sources. The results stress the importance of proper polarization management in a high resolution OCT/OCM system. The employed small-footprint combined-SLED source using micro optics mitigates this drawback due to intrinsic polarization alignment of all individual SLEDs. Therefore, no additional optical equipment (such as a polarizer) is necessary for OCM and OCT, which increases the available optical power, maintains the spectral shape and decreases system complexity. In addition to the proper polarization management, SLEDs have the general advantage of being maintenance free, featuring long lifetimes and low random intensity noise, which make them attractive sources for high-resolution OCM and OCT.

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