Multi-spectral bands optical coherence tomography assisted by ultrawide band photonic crystal fiber splitter

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\begin{abstract}
We report fabrication and performance of the $2 \times 2$ photonic crystal fiber (PCF) splitter that enables multi-spectral bands operation of an optical coherence tomography (OCT) system. The PCF splitter was made by coupling PCFs to a planar lightwave circuit (PLC) splitter chip, which worked as a single mode splitter from visible to near infrared wavelengths. The core size of the PLC splitter chip was about $3 \mu m \times 3 \mu m$ and the core-cladding index difference was about 0.25%, which gave the cutoff wavelength at 630 nm. The implemented PCF-PLC splitter showed a small excess loss of 1.2 – 3.3 dB and a low polarization-dependent loss (PDL) of 0.15 – 0.19 dB over a wide wavelength range from 640 nm to 1000 nm. With the splitter, OCT images of a human finger and a nail have been successfully obtained at several spectral bands; 680 nm, 840 nm, and 930 nm center wavelengths.
\end{abstract}

\section{1. Introduction}

Optical coherence tomography (OCT) has been widely studied owing to its noninvasive imaging capability. OCT has provided highly sophisticated tomographic images of biological samples based on low coherence interferometry \cite{1}. In general, a wide band optical source allows implementing a high axial resolution OCT system \cite{2}. Recently, a dual spectral band OCT system was reported, which was used to investigate the wavelength-dependent probing depth and imaging quality in a dense tissue \cite{3}. As a wide band source, superluminescent light-emitting diode (SLD) is most commonly used because it is compact and relatively inexpensive. Moreover, white light source \cite{4}, short pulse laser \cite{5}, and super-continuum source \cite{6} have been used also.

Though many kinds of broadband light sources are available, there is spectral bandwidth limitation in utilizing them for fiber-based OCT systems. In general, a conventional single mode fiber (SMF) coupler has a single mode cutoff wavelength for the un-symmetrically deformed air hole configuration of the PCF give a high excess loss of 3–6 dB due to the damage or contamination of the air holes in the PCF during the fabrication process. Furthermore, the un-symmetrically deformed air hole configuration of the PCF caused optical power fluctuation and increased its polarization dependent loss (PDL). A $2 \times 2$ PCF planar lightwave circuit (PLC) splitter could overcome the shortcomings of the PCF couplers; however, the conventional splitter PLC chip has the single mode cutoff wavelength at longer than 1200 nm \cite{10}. Furthermore, the spectral domain OCT (SD-OCT) system operating at longer than 1000 nm is not cost effective due to the high price of an InGaAs-based line CCD. Dual and multi-spectral bands SD-OCT systems have been also presented for getting wavelength dependant OCT images, but these systems were bulky and expensive due to using bulk optics and the InGaAs line CCD \cite{11}.

In order to make a cost effective but operating at multi-spectral bands SD-OCT system, new fiber devices having the single mode operation at wavelengths shorter than 1000 nm, wide spectral bandwidth, and low excess loss are necessary. Beside high reproducibility, the silica-based PLC splitters are well known as having the advantages of low loss, compact size, low PDL, and low coupling loss \cite{12}. In this paper, we report the $2 \times 2$ PCF-PLC splitter having single mode operation at both visible and near infrared wavelengths, and present the performance of the multi-bands SD-OCT system that is equipped with the proposed splitter. The fabrication process and the coupling characteristic of an implemented $2 \times 2$ PCF-PLC splitter are presented and discussed. To confirm the

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\end{keywords}
operation of the proposed splitter, we present a series of SD-OCT images of human finger and nail taken at three spectral bands; 680 nm (8 nm 3 dB bandwidth), 840 nm (50 nm 3 dB bandwidth), and 930 nm (65 nm 3 dB bandwidth), respectively.

2. Design and fabrication of 2 × 2 PCF-PLC splitter

The endless single mode PCF (LMA-5, NKT Photonics) used for experiments had 6 layers of air holes around a 5 μm diameter silica core, and the cladding diameter was 125 μm. As shown in Fig. 1(a), PCFs were placed in the V-grooves of a silicon block and then covered with a quartz plate. To secure the fixation, UV epoxy was applied between the silicon block and the quartz plate. Fig. 1(a) is a microscope side view image of the PCF array block loaded with two PCF pieces. The PCF array block was designed for holding two 125 μm fibers separated by 250 μm at each side, and the V-grooves were lithographically fabricated. The end faces of the PCF fiber array blocks and the PLC splitter were polished with a tilt angle of 8° for increasing return loss. A wavelength-insensitive coupler (WINC) was designed with the PLC configuration of Fig. 1(b). The coupler consists of a single stage Mach–Zehnder interferometer; it has two directional couplers (C1 and C2) connected by two waveguide arms but with a small path length different of ΔL [13,14]. The wavelength dependence of the power coupling ratio $P_2(λ)$ for input port 1 of WINC is given as [14]

$$P_2(λ) = \cos^2\left(\frac{β(λ)ΔL}{2}\right)\sin^2(θ_1(λ) + θ_2(λ)) + \sin^2\left(\frac{β(λ)ΔL}{2}\right)\sin^2(θ_1(λ) − θ_2(λ))$$  \hspace{1cm} (1)

with,

$$θ_1(λ) = \frac{π}{2} \frac{L_1 + Δh(λ)}{L_1(λ)}$$

$$θ_2(λ) = \frac{π}{2} \frac{L_2 + Δh(λ)}{L_2(λ)}$$  \hspace{1cm} (2)

In these equations $β(λ)$ is the propagation constant of the waveguide, wavelength dependent in general, and $θ_1(λ)$ and $θ_2(λ)$ are angular expressions of the amplitude coupling ratios of directional coupler C1 and C2, respectively. Furthermore, $L_0(λ)$ is a complete coupling length of the directional coupler; $L_1$ and $L_2$ are the straight part lengths of the two directional couplers. The coupling effect in the curved parts of directional couplers is

Fig. 1. Microscope image of an implemented PCF array block (a), and the configuration of a wavelength-insensitive directional fiber coupler composed of a single stage Mach–Zehnder interferometer (b). Two PCF block arrays to the PLC chip connection procedure with UV curable.

Fig. 2. Calculated wavelength response of the normalized power (a), and the excess loss (b) of the proposed splitter.
considered as an effective length $\Delta l(l)$. Then, the wavelength-insensitive transmittance can be achieved by optimizing the three circuit parameters $L_1$, $L_2$, and $\Delta L$.

By using a numerical calculation with a conventional simulation tool (Olymio, Thermo scientific) we optimized the parameters that could make the coupling ratio of the WINC as much flat as possible at both visible and near infrared wavelengths. The calculated wavelength response of the normalized power for each output port is shown in Fig. 2(a). The core size of the PLC waveguide was $3 \mu m \times 3 \mu m$ and $d$ (index difference between core and cladding) was 0.25%. The obtained optimum parameters were $\Delta L=0.73 \mu m$, $L_1=450 \mu m$, $L_2=800 \mu m$, and the bending radius was about 140 mm. Fig. 2(b) is the excess loss of the waveguide circuit calculated with two bending radii, 120 mm and 140 mm. The larger bending radius gave the lower excess loss of course.

The splitter chip was fabricated by using the conventional fabrication method, and polished with a tilt angle of 8°. The PCF array blocks and the splitter were well aligned and connected together with UV curable adhesive as shown in Fig. 1(c). For portability and usability, both input and output fibers of the PCF-PLC splitter were terminated with FC/APC connectors having low back reflection. During the connector packaging process, great attention was made not to contaminate the air holes of the PCFs, which were easily clogged by the polishing powder. The total insertion loss, mainly caused by the air hole contamination, was about 1 dB. The insertion loss could be reduced appreciably by reducing the air hole contamination at least in principle. One of the possible approaches is splicing a very short piece of coreless silica fiber at the endface of each PCF before polishing it. We hope to try this engineering effort in near future.

The transmission spectrum of the fabricated PCF-PLC splitter was measured by using 680, 840, and 1040 nm SLDs and an optical spectrum analyzer (OSA; ANDO, AQ6317B). Fig. 3 shows the transmission spectra (left column) and the power splitting ratio (right column) measured at both through (black and solid curve) and cross (red and dotted curve) channels of the PCF-PLC splitter. We can see that the coupling ratio was quite flat over a wide wavelength range from 640 nm to 1100 nm. The PLC splitter chip was designed to be single mode with a 630 nm cutoff wavelength. The coupling ratio of the PCF-PLC splitter was compared with that of the PCF-PLC splitter.
of a conventional 630 nm SMF coupler in Fig. 4. As Fig. 4(a) shows the SMF coupler had a coupling ratio varying from 10% to 90% within a 100 nm bandwidth centered at 680 nm. Further worse, no power coupling was observed at the 840 nm wavelength band as shown with Fig. 4(c). However, as Fig. 4(b) and (d) show, the PCF-PLC splitter had a quite flat splitting ratio over the 100 nm bandwidth at 680 nm center wavelength, and also show rather flat coupling at 840 nm band. The PDLs of the SMF coupler and the PCF-PLC splitter were measured at 850 nm and 635 nm wavelengths by using a single mode VCSEL (Vertical-cavity surface-emitting laser, Newfocus), a 635 nm laser diode (S1FC635, Thorlabs), two polarization controllers (680 nm and 840 nm center wavelengths, General photonics), and an optical power meter (1930-IS, Newport). We measured the optical power deviation with various polarization states by using the polarization controllers and the optical power meter. PDL of the PCF-PLC splitter was 0.19 dB, which was less than half of the SMF coupler, 0.40 dB at 850 nm. At 630 nm, PDLs of the PCF-PLC splitter was 0.15 dB but the conventional SMF coupler showed nearly 0.49 dB. However, the PCF-PLC splitter had a higher excess loss than that of the SMF coupler.

3. Configuration of multi-spectral bands SD-OCT based on wide band PCF-PLC

The brief schematic of the SD-OCT system equipped with the proposing PCF-PLC splitter is shown in Fig. 5. The light beams from three SLDs were launched into the input port of the 2 x 2 PCF-PLC splitter one by one, and then split into the reference and the sample arm ports. The beams back reflected from the reference mirror and from a sample were recombined and interfered with each other at the detection port of the coupler. The interference spectrum, then, was measured by the spectrometer and data processed with a personal computer. The home-made spectrometer consisted of a grating, focusing lens, and array sensor. The grating of the spectrometer was replaced according the wavelength range of each SLD.

The interference spectra dispersed by three volume phase holographic transmission gratings ($\lambda_c$=680 nm, 840 nm, and 930 nm with 1200 lines/mm) were detected by one 2048 line CCD, after focusing with a common achromatic doublet lens. The interference spectrum measured in the wavelength domain was transformed into the wave number domain by means of the signal processing called rescaling processing [15]. Since there is non-linear relationship between the wavelength and the wave-number, the interference spectrum data points were interpolated [16–17]. Finally, the depth information of the sample was obtained by performing an inverse fast Fourier transform (IFFT). The free-space axial resolution of the implemented OCT system was measured as the full-width at half maximum (FWHM) of the A-scan peak. It was 31.3 $\mu$m with the 680 nm SLD, 7.6 $\mu$m with the 840 nm SLD, and 6.4 $\mu$m with the 930 nm one.

4. Imaging performance of the multi-spectral bands SD-OCT system

To confirm the multi-spectral bands imaging performance of the implemented SD-OCT system, based on the proposing
PCF-PLC splitter, we have imaged human finger and finger nail. The prepared three SLDs and the corresponding three gratings having different center wavelengths (680 nm, 840 nm, and 930 nm) were used one by one without changing any other system component. Fig. 6 shows the 3D images of an in vivo human finger (a little finger) taken at 680 nm (a), 840 nm (b), and 930 nm (c) spectral bands. Each image presents an area of 4 mm (x-axis) × 1.2 mm (y-axis) × 1.5 mm (z-axis). Interestingly, the image at 930 nm (c) clearly shows the veins of the finger, while the one at 680 nm (a) barely shows them. Even though, the axial resolution at 680 nm was much poor due to the narrow bandwidth of that SLD, Fig. 6 clearly shows that the imaging at infrared spectral bands gives deeper imaging depth than that of the one made at visible band.

Fig. 7(a) shows the 3D image of a human finger nail taken at the band of 840 nm. The 2D cross-sectional images of the same sample but taken at different bands are shown with Fig. 7(b) (680 nm), 7(c) (840 nm), and 7(d) (930 nm). The layer structures within the nail plate can be identified with the 840 nm and 930 nm bands. However, unfortunately, at 680 nm band, the layer of the fingernail was not seen clearly. It might be due to the low axial resolution and the poor penetration at the 680 nm band. Compared to the 930 nm image, the distance between the dark layers in the nail plate was a little shorter than that at the 840 nm.

![Fig. 6. OCT images of human finger at 680 nm (a), 840 nm (b), and 930 nm (c) wavelength, respectively.](image)

![Fig. 7. 3D OCT image of a human finger nail taken at the 840 nm band (a), and 2D OCT images (x-z) of the same sample taken at the band of 680 nm (b), 840 nm (c), and 930 nm (d), respectively.](image)
The distance between the dark layers of the human nail should be proportional to the wavelength of the applied light if the imaging is mostly influenced by sample birefringence [11].

5. Discussion and conclusions

Through the OCT imaging of human finger and nail at three different spectral bands, we could show the possibility of fiber-based multi-bands SD-OCT system operating at both visible and near infrared wavelengths. Because the PCF-PLC splitter fabricated for this experiment operates from 630 nm to 1100 nm, this scheme can be adopted to the system based on a femto-second laser or a supercontinuum source. Therefore, we can expect practical applications in the field of high resolution OCT or OCM (optical coherence microscopy) with a wideband spectrometer [18], and fiber-based convergence imaging systems such as the system combining OCT and multi photon microscopy (MPM).

A single mode 2 × 2 PCF-PLC splitter implemented by connecting PCFs to a PLC splitter and operating at both visible and near infrared wavelengths, has been presented. By using lithographically fabricated V-grooves, PCFs were fixed at PCF array blocks. By optimizing the fabrication parameters of a waveguide circuit, the wavelength-insensitive coupler (WINC) having a rather flat coupling ratio over visible and near infrared wavelengths could be fabricated. The fabricated PCF array blocks and the splitter chip were aligned and connected together with UV curable adhesive. The optical performances of the proposed device, including low FDL and wide band flat coupling ratio, were concluded as better than those of conventional 840 nm and 630 nm SMF couplers. Owing to the help of the proposed PCF-PLC splitter, the OCT images of human finger and finger nail were successfully obtained at various spectral bands without changing any system component.

Since the flat coupling bandwidth and the cutoff wavelength of the PCF-PLC splitter can be adjusted by controlling the coupling length, index difference, and the path length difference of the splitter chip, we can expect a wider band fiber splitter also. Therefore, we might find good applications especially in the fields of fiber-based high resolution OCT and OCM with a supercontinuum or multi wavelength swept source. We can think of implementing the convergence system of OCT and MPM.

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