PLC-based eight-channel OFDM demultiplexer and its demonstration with 160 Gbit/s signal reception

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Abstract: An integrated-optic demultiplexer for 8 x 10 Gbaud OFDM sub-carrier channels is realized, which comprises a PLC-based 8 x 8 optical FFT circuit. It is successfully used to demultiplex a 160 Gbit/s OFDM signal optically.

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1. Introduction

The research and development of optical orthogonal frequency division multiplexing (OFDM) technology, which generates and transmits sub-carriers that are orthogonal to each other, is being vigorously pursued because of its merits, which include a high spectral efficiency and tolerance to chromatic and polarization-mode dispersion in fibers [1]-[5]. The channels cannot be demultiplexed with conventional optical frequency filters because the channel spectra overlap, and a discrete Fourier transform (DFT) procedure is indispensable for demultiplexing the channels at the receiver. An electrical demultiplexing scheme based on digital signal processing is being actively investigated. But off-line processing has become the main approach for OFDM [4], and the real-time processing speed is limited to several Gbit/s [5]. In contrast, an optical scheme can easily process OFDM signals at tens of Gbit/s [1], [2]. We proposed a device for demultiplexing OFDM channels directly in the optical domain based on an optical fast Fourier transform (FFT) circuit and fabricated with silica planar lightwave circuit (PLC) technology [3]. The device can process a large number of OFDM channels with less computational complexity and a much simpler configuration than a device based on optical DFT [1]. We demonstrated its operation and effectiveness by demultiplexing 4 x 10 Gbit/s signals with a 4 x 4 FFT circuit [3].

In this paper, we describe a device for demultiplexing 8 x 10 Gbaud OFDM channels in the optical domain. The device consists mainly of a PLC-based 8 x 8 FFT circuit. The 8 x 8 FFT circuit is formed by combining two 4 x 4 FFT circuits, which makes its design and configuration simple, and we reduced the power consumption of the device by trimming thermo-optic (TO) phase shifters. Thus we realized the 8 x 8 version for the first time. We verified the operation and effectiveness of the devices by measuring the bit error rates (BERs) of demultiplexed signals from a polarization multiplexed 160 Gbit/s OFDM signal with a spectral efficiency of 2 bit/s/Hz, and we showed their applicability to transmission systems operating at over 100 Gbit/s.

2. Device configuration

Sub-carrier signals $d_n(t)$ (n=0 to N-1) are demultiplexed from an OFDM signal S(t) with the following DFT [1].

$$d_n(t) = \sum_{g=0}^{N-1} S(g\Delta t) e^{-j\frac{2\pi Tg}{N}\left(f_0+\frac{n}{T}\right)}, \quad \Delta t = \frac{T}{N}, \qquad (1)$$

where f_0 and T are the carrier frequency of $d_0(t)$ and the bit period of each sub-carrier signal, respectively. Equation (1) is also expressed with an N x N matrix none of whose elements is zero. To realize this matrix with optical circuits requires N 1 x N splitters and N x 1 combiners, and N^2 connecting waveguides for the splitters and the combiners, which makes the configuration large and complex. When N is eight, the DFT in Eq. (1) is modified to an FFT as shown in the following equation, which simplifies the device configuration.

$$\begin{pmatrix} d_0(t) \\ d_4(t) \\ d_2(t) \\ d_6(t) \\ d_1(t) \\ d_5(t) \\ d_3(t) \\ d_7(t) \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -j & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & j & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & e^{-j\pi/4} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -e^{-j\pi/4} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -e^{j\pi/4} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & e^{j\pi/4} \end{pmatrix} \begin{pmatrix} [S1(0)+S1(4\Delta t)]+[S1(2\Delta t)+S1(6\Delta t)] \\ [S1(\Delta t)+S1(5\Delta t)]+[S1(3\Delta t)+S1(7\Delta t)] \\ [S1(0)+S1(4\Delta t)]-[S1(2\Delta t)+S1(6\Delta t)] \\ [S1(\Delta t)+S1(5\Delta t)]-[S1(3\Delta t)+S1(7\Delta t)] \\ [S1(0)-S1(4\Delta t)]-j[S1(2\Delta t)-S1(6\Delta t)] \\ [S1(\Delta t)-S1(5\Delta t)]-j[S1(3\Delta t)-S1(7\Delta t)] \\ [S1(0)-S1(4\Delta t)]+j[S1(2\Delta t)-S1(6\Delta t)] \\ [S1(\Delta t)-S1(5\Delta t)]+j[S1(3\Delta t)-S1(7\Delta t)] \end{pmatrix}, \quad S1(g\Delta t) = S(g\Delta t)e^{-jg\pi f_0 T/4}. \qquad (2)$$

Figure 1 shows the configuration of our demultiplexer for an 8 x 10 Gbaud OFDM signal, which is composed of a

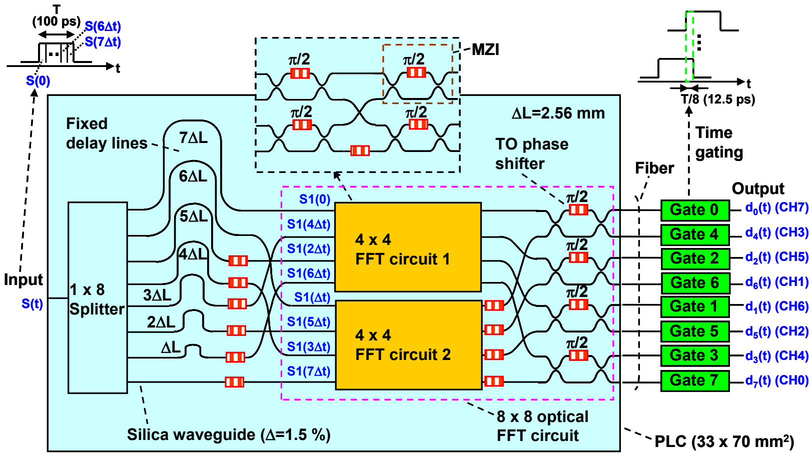

Fig. 1. Configuration of demultiplexer for 8 x 10 Gbaud OFDM sub-carrier channels.

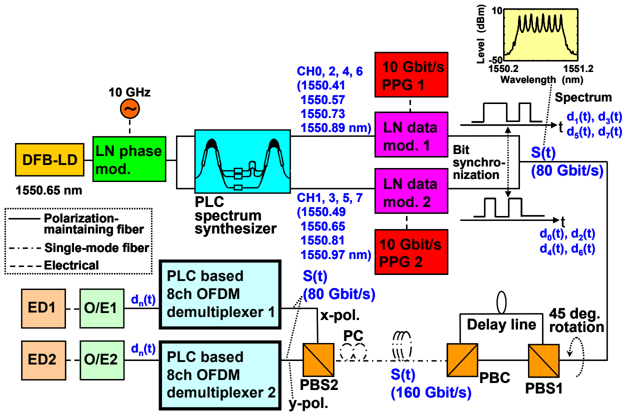

Fig. 2. Experimental setup for evaluating OFDM demultiplexers for polarization multiplexed 160 Gbit/s OFDM signal.

silica PLC filter with a relative index difference Δ of 1.5 % (a 1 x 8 splitter, eight fixed delay lines, and an 8 x 8 optical FFT circuit) and electro-absorption (EA) modulator based optical gates that are attached to the filter through fibers. The PLC core and chip size are 4.5 x 4.5 μm^2 and 33 x 70 mm^2, respectively. The 8 x 8 FFT circuit is composed of two 4 x 4 FFT circuits and an array of four Mach-Zehnder interferometers (MZIs). The OFDM signal S(t) input into the PLC filter is split into eight signals that are relatively delayed by integer times of Δt with a view to obtaining the signal S1(gΔt) (g=0 to 7), where Δt=ΔL/c (c: light speed in the waveguide). A symmetrical MZI with a phase shift ϕ of π/2 outputs the addition and subtraction of two input signals, and the right and left matrices at the product of the two matrices in Eq. (2) correspond to the transfer functions of the 4 x 4 FFT circuits and the array of four MZIs with additional phase shifters at their inputs, respectively [3]. An N x N FFT can easily be calculated by the butterfly computation of two sets of N/2 x N/2 FFTs. This mathematical property makes the filter design and configuration simple, thus a large-scale FFT circuit can be simply composed by using units consisting of smaller scale FFT circuits. To demultiplex each sub-carrier channel completely, we need to extract the period T/8 (12.5 ps), where the same S1(t) bits overlap, with the optical gates. The data eye patterns are only open during this period, because the orthogonal property between the sub-carrier channels is maintained within a one-bit period. This large-scale PLC filter has several points at which waveguides intersect that induce crosstalk and extra loss. To overcome these defects, we adopted a tapered waveguide whose width was adiabatically increased from 4.5 to 9.0 μm at the intersection. Also, there are tens of phase shifters that must be precisely adjusted. We added a predetermined phase shift to the waveguide by adjusting the waveguide length, and trimmed the residual phase error by applying local heating and quenching with high electrical power [6] to a TO thin film heater. Thus the total operational TO phase shift power was reduced to less than 1 W.

3. Experimental results

Figure 2 shows our experimental setup for evaluating the OFDM demultiplexers. We generated 10 GHz-spaced frequency combs with a $LiNbO_3$ (LN) phase modulator, and equalized their intensity variation to less than 3.0 dB with a PLC spectrum synthesizer [7] as indicated in Fig. 2. The odd and even wavelength channels were modulated with different LN intensity modulators. The intensity modulators were driven with two sequences of non-return-to-zero 10 Gbit/s binary data from two synchronized pulse pattern generators (PPGs) so that adjacent channels are decorrelated. The two sets of modulated lights were combined after adjusting their bit synchronization by tuning the RF phase difference between the PPG outputs. These procedures correspond to an inverse DFT of the sub-carrier signals $d_n(t)$ (n=0 to 7), and generated an 8 x 10 Gbit/s OFDM signal. Then the signal was coupled to the axis of a polarization beam splitter (PBS1) at an angle of 45 degrees, thus creating two orthogonally polarized 80 Gbit/s signals. The signals were recombined with a polarization beam combiner (PBC) to produce a polarization multiplexed 160 Gbit/s OFDM signal. A delay line between the PBS1 and the PBC was used to decorrelate the two 80 Gbit/s signals. The 160 Gbit/s signal was converted into two 80 Gbit/s signals with a polarization controller (PC) and PBS2, and the two signals were introduced into the two OFDM demultiplexers. The BERs of sixteen demultiplexed sub-carrier signals were evaluated with an error detector (ED).

Figure 3 (a) and (b) show the measured transmittance spectra of all the channels and CH4 of the PLC filter in Fig. 1, respectively. Figure 3 (b) also shows the calculation for comparison. The calculation indicates that the filter has a bandwidth of about 10 GHz at the demultiplexed channel and steep extinction characteristics of more than 40 dB between the demultiplexed and the unwanted channels. The measured characteristics agreed well with the calculation and their extinction ratios were around 20 to 30 dB. The fiber-to-fiber losses of all the channels were 2.5 to 2.8 dB. Figure 4 shows the BERs of both polarization signals in CH6 measured under a back-to-back condition. The closed circles indicate the reference BER when only CH6 signal was input. We were able to achieve an error rate of the order of 10^{-9} for all sixteen demultiplexed channels, and the power penalties compared with the reference were 0.8 to 2.6 dB at BERs of 10^{-9} as summarized in Table 1. These results confirm that we were able to demultiplex a desired channel from among a polarization multiplexed 160 Gbit/s OFDM signal with a spectral efficiency of 2 bit/s/Hz by using our OFDM demultiplexers for eight channels. The power penalties were mainly caused by the crosstalk of other channels owing to the imperfect operation of the PLC filter and EA gates.

4. Summary

We realized a device for demultiplexing 8 x 10 Gbaud OFDM sub-carrier channels directly in the optical domain. The device consists of a silica PLC based 8 x 8 FFT circuit and EA gates. We successfully demultiplexed a polarization multiplexed 160 Gbit/s OFDM signal with spectral efficiency of 2 bit/s/Hz by using the two demultiplexers, and showed their applicability to transmission systems operating at over 100 Gbit/s.

5. References

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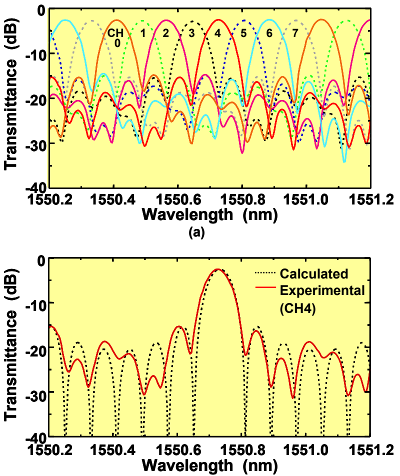

Fig. 3. Specra of (a) all channels and (b) CH4.

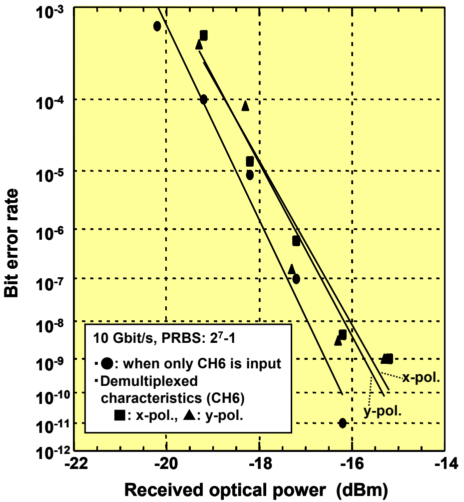

Fig. 4. Measured BERs.

Table 1. Summary of power penalties.

CH No.	Power penalty at BER=10^{-9} (x-pol.)	Power penalty at BER=10^{-9} (y-pol.)
0	1.4	0.9
1	2.0	2.2
2	2.6	2.2
3	0.9	1.4
4	2.1	2.2
5	0.9	1.6
6	1.0	0.8
7	1.3	1.7