100 Gbit/s Compact Digital Coherent Receiver Using InP-based Mixer

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For next generation digital coherent optical transmission systems, compact transceivers like CFP (100G Form-factor Pluggable) or CFP2 form factor have been highly anticipated. The authors have successfully developed a compact digital coherent receiver for such applications. The InP-based MMI (Multi-Mode Interferometer)-mixer chip integrated with photodiodes (PDs) is the key element in fabricating a compact receiver module. The transmission performance of the prototype is same as a conventional large form factor receiver.

Keywords: coherent receiver, MMI, DP-QPSK, mixer, PD

1. Introduction

Multi-level modulation formats, such as dual polarization quadrature phase-shift keying (DP-QPSK[*1]), using coherent detection with digital signal processing (DSP), has been put to practical use in recent optical communication systems to deal with the explosive increase of data traffic demand.

The intradyne coherent receiver is one of the key optical devices used in such coherent optical communication systems. Currently OIF[*2] compliant coherent receivers are widely used in OIF compliant transponders and proprietary line-cards. The maximum package size is defined as 27 mm x 50 mm x 9 mm.

For next generation coherent systems, compact transceivers like CFP or CFP2[*3] form factor have been highly anticipated. Smaller coherent receivers are needed for these applications, since OIF compliant receivers are too large to be installed in CFP or CFP2 transceivers (**Fig. 1**).

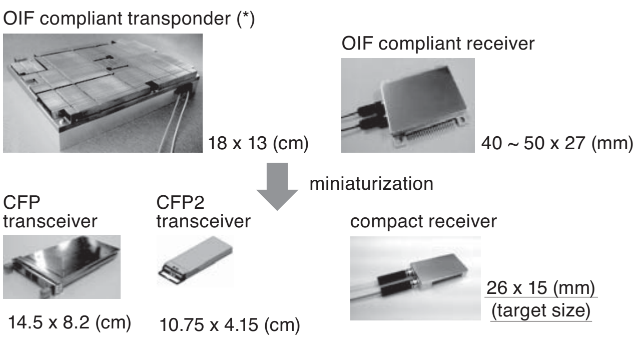

Fig. 1. Size of transceivers and receivers

(*Source: NEC Corporation, web site, press release on July 25, 2011)

In this paper, we report on the development status of a compact coherent receiver that uses an InP-based mixer integrated with PDs[(1), (2)].

2. Development Target and Specifications

The target size of the receiver is set at 26 mm x 15 mm x 5.5 mm. This is small enough to be installed in CFP2 transceivers. The main target characteristics are shown below, in **Table 1**.

Table 1. Target specification

Parameter	Min.	Typ.	Max.	Unit	Comment
Temperature range	0	-	75	˚C	
Wavelength	191.15 1528.77	-	196.1 1568.36	THz nm	
Responsivity	50	-	90	mA/W	Local Oscillator
	40		80		Signal
Bandwidth	22	-		GHz	
CMRR[*4]	-	-	-20	dBe	DC

3. Challenge in Receiver Miniaturization

In order to meet the challenge of miniaturizing a receiver, the internal structure and the operating principles of a coherent receiver are first examined.

A block diagram of a coherent receiver is shown in **Fig. 2**. This structure is known as a polarization and phase diversity coherent receiver. An input signal light is first demultiplexed to two orthogonal polarized lights by a polarization beam splitter (PBS). Then each polarized light and local oscillator (LO) light is mixed at a mixer[*5] (also known as 90 degree hybrid) to detect the phase and amplitude in a signal light. PDs are located at the output of the mixer for optical to electrical signal conversion.

A silica-based planar lightwave circuit (PLC) is conventionally used as a mixer due to its mature technology. In papers published in 2012 and before, a mixer size of 144 mm^2[(3)]

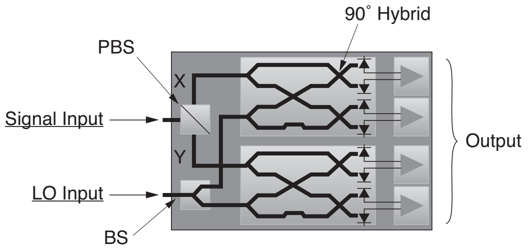

Fig. 2. Block diagram of coherent receiver

and 266 mm^{2}[(4)] was reported. These sizes include a PBS and a BS. This large size of the silica-based mixer is the main obstacle in creating compact coherent receivers.

Most of the mixer area in silica-based PLCs is occupied by bending waveguides. The difficulty in designing smaller mixers is the fact that the lower limit of the waveguide bending radius is mainly determined by refractive index difference of a waveguide.

InP-based waveguides usually have a higher refractive index difference than a silica-based one. Therefore, a smaller mixer size could be created, since waveguides with a smaller bending radius could be used. We have developed a compact coherent receiver using an InP-based mixer chip.

4. InP-based Mixer with Integrated PD

The InP-based mixer consists of a 2 x 4 multi-mode interferometer (MMI) and a 2 x 2 MMI. The MMI waveguide has a GaInAsP core layer on an InP substrate. Four waveguide photodiodes (PDs), which have a GaInAs absorption layer, are monolithically integrated. Capacitors at PD bias are also integrated (**Fig. 3**).

The waveguide section with the GaInAsP core layer and the PD section were connected by the butt-joint process to achieve high responsivity. The chip size is very small, at 2.0 mm x 5.1 mm.

The optical-electrical responses for the four PDs are shown in **Fig. 4**. A 3 dB bandwidth is more than 20 GHz. Uniform characteristics of over four PDs were achieved.

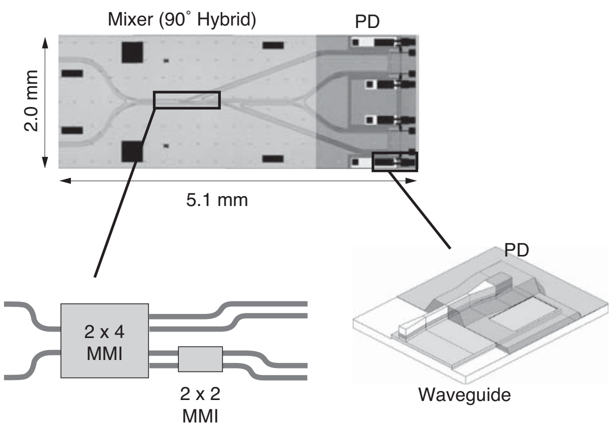

Fig. 3. InP-based mixer with integrated PD

A transmittance spectrum for mixers is shown in **Fig. 5**. A loss variation of less than about 1 dB has been achieved in a wavelength range from 1530 to 1570 nm.

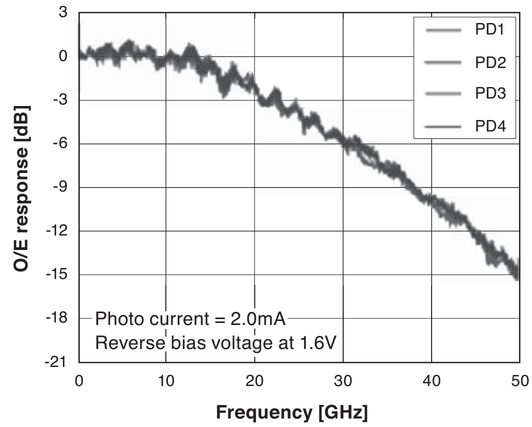

Fig. 4. Optical/Electrical response

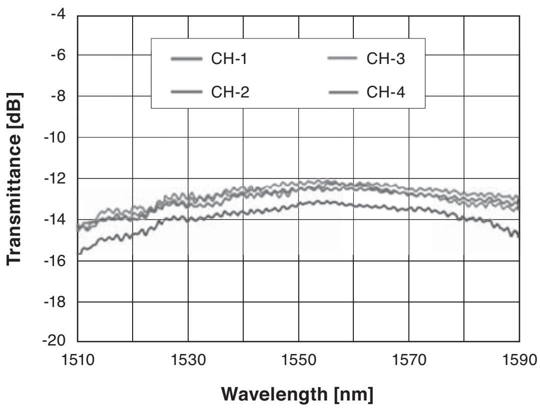

Fig. 5. Transmittance spectra

5. Receiver Design

The structure of a receiver is shown in **Fig. 6**.

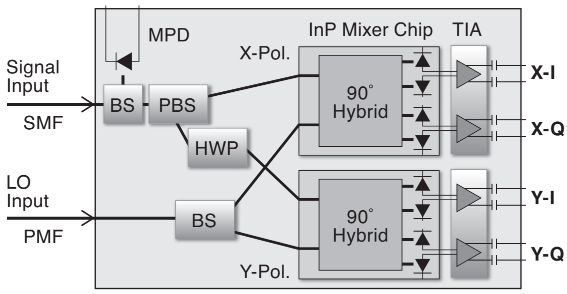

Fig. 6. Structure of receiver

The optical coupling between the optical fibers and the InP-based mixer chip has been constructed with micro optics. The signal light, which has arbitrary polarization, is introduced to the receiver by a single mode fiber (SMF). At first, the light from the SMF goes to the collimate lens to make collimate light[*7]. Then, a small portion of the signal light is split to monitor photodiode (MPD) via the BS. At the PBS, the signal light is decomposed to transverse electric (TE) polarized light and transverse magnetic (TM) polarized light. The TE polarized light is coupled to the InP-based mixer for X-polarization by the lens. The TM polarized light is converted to TE polarized light by the Half Wave Plate (HWP). Then this TE polarized light is coupled to the InP-based mixer for Y polarization by the lens. The local oscillator light is introduced to the receiver through a polarization maintaining fiber (PMF). The slow axis of the PMF is aligned to the TE polarized light. The PMF angle is precisely controlled and fixed so that the TE polarized light is incident to the BS. At first the light from the PMF goes to the collimate lens, and then is split by the BS. Finally the light is coupled to the InP-based mixer for X-polarization and that for Y-polarization by the lens.

The electrical connections between the photodiodes and TIAs[*8], and between the PDs and the bias circuit are made by conventional gold wire bonding. Due to having an integrated on-chip bypass capacitor for each PD in the InP-based mixer, superior RF characteristics have been achieved, as well as size and cost reduction through the elimination of external bypass capacitors for PD bias lines. TIA outputs are connected to 4-ch GSSG output leads at the back side of the package through the DC-blocks. DC bias pins for PDs and TIAs and TIA control pins are located at the left and right side of the package. The package is hermetically sealed to ensure long-term reliability.

Package comparison between conventional OIF compliant recievers and the compact reciever is shown in **Fig. 7**.

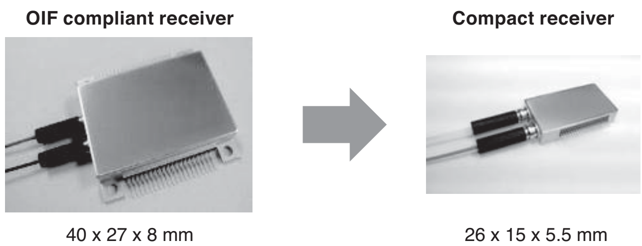

Fig. 7. Receiver package comparison

A package size of 26 mm x 15 mm x 5.5 mm was developed in the compact receiver. This size is small enough to be installed in a CFP2 transceiver. Compared to OIF compliant receivers, the foot print is about 1 / 3 in size.

6. DC Characteristics

We have also evaluated compact coherent receiver samples. First, average responsivity has been measured. An average responsivity of about 60 mA/W was obtained from 1530 nm to 1570 nm at the signal input (**Fig. 8**).

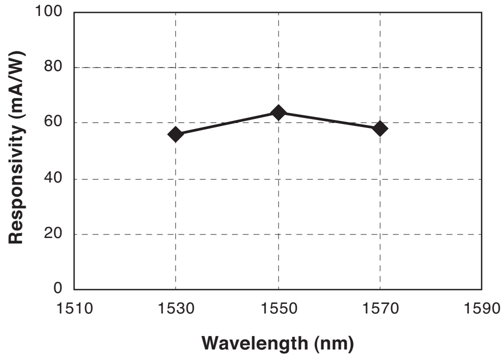

Fig. 8. Responsivity wavelength dependence

Then imbalance, which is defined as the responsivity ratio difference between pair PDs, has been measured. The temperature dependence of the imbalance is shown in **Fig. 9**.

The imbalance is less than 0.3 dBo and has little temperature dependence.

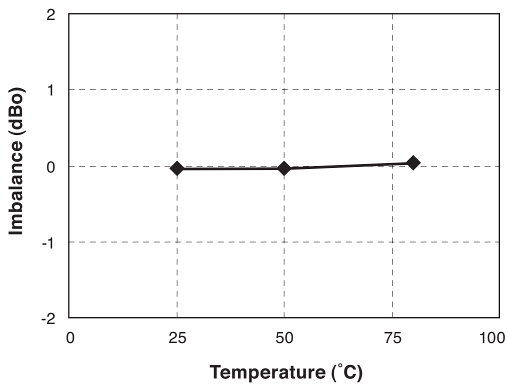

Fig. 9. Imbalance temperature dependence

7. RF Characteristics

The small signal frequency response is shown in **Fig. 10**.

In **Fig. 10**, the magnitude is normalized through the low frequency region. Since a TIA has bandwidth adjust-

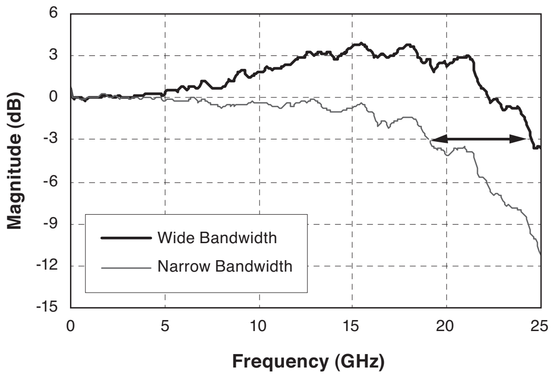

Fig. 10. Frequency response

ment capability, the frequency response at maximum bandwidth setting and at minimum bandwidth setting is both shown. At maximum bandwidth setting, a 3 dB bandwidth of more than 24 GHz is achieved. At minimum bandwidth setting, the 3 dB bandwidth could be reduced to 19 GHz.

Figure 11 shows the measurement result of CMRR which indicates the capability of removing an unnecessary common-mode signal.

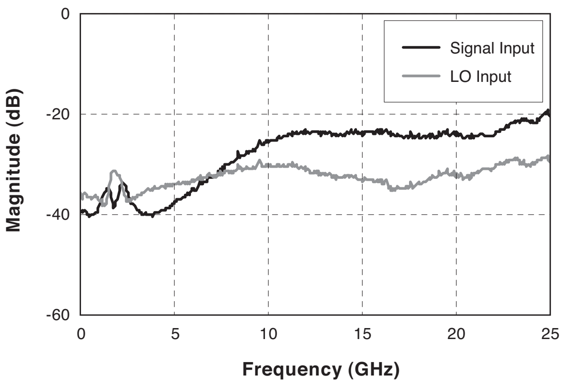

Fig. 11. CMRR frequency dependence

A CMRR of less than -20 dB, up to 25 GHz, has been achieved. It indicates that good responsivity matching and low skew[*9] are achieved between the two PDs pair.

8. Transmission Characteristics

The comprehensive device performance has been evaluated by transmission test using a 128 Gbit/s DP-QPSK modulated signal. A pseudorandom binary sequence data of 2^9-1 and 2^{11}-1 is used for two orthogonal polarizations. A 50 GSamples/sec high-speed sampling oscilloscope is used as the ADC. The signal input power is -10 dBm. The LO input power is +10 dBm. The wavelength is 1550.1 nm. The positive output port of each TIA is connected to the oscilloscope input. The negative output port is connected to the 50 ohm load. The single-ended output swing of the TIA is set at about 350 mVpp. The oscilloscope simultaneously samples four channels, which are X-I, X-Q, Y-I, and Y-Q data. The acquired sampling data is processed offline to demodulate the DP-QPSK signal.

Figure 12 shows the constellation diagram[*10] for X and Y polarization at an optical signal-to-noise ratio (OSNR) of 20 dB. In the OSNR measurement, 0.1 nm optical bandwidth is applied. Clear segregation among each symbol has been measured. It indicates that successful transmission has been achieved. **Figure 13** shows the back-to-back bit error rate (BER) vs. OSNR for X and Y polarization. The obtained OSNR performance also indicates successfull transmission.

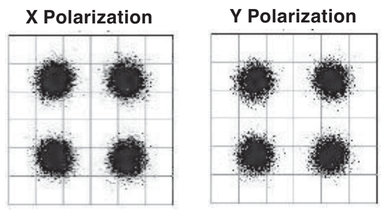

Fig. 12. Constellation

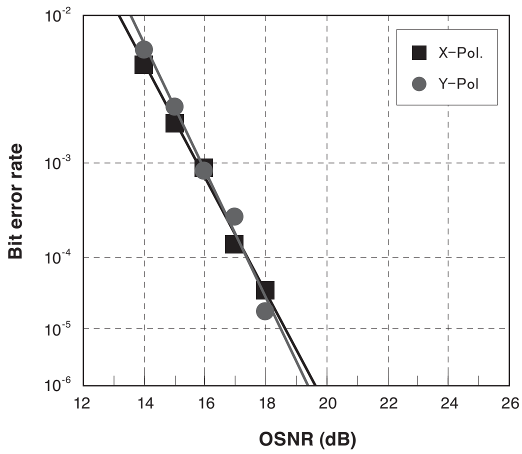

Fig. 13. BER vs. OSNR curve

9. Conclusion

A 100 Gbit/s compact digital coherent receiver using an InP-based mixer integrated with PDs has been reported. The package size is 26mm x 15mm x 5.5 mm. This size is small enough to be installed in a CFP2 transceiver. 128 Gbit/s DP-QPSK transmission tests have been successfully conducted. These results indicate that this receiver is a very attractive device for future digital coherent transmission systems.

Technical Terms

*1 DP-QPSK (Dual Polarization-Quadrature Phase Shift Keying): QPSK is a modulation method that uses 4 phase states, which are 0, 90, 180, 270 degrees, to transmit 2 bit information at a single time slot. DP means that a signal is multiplexed by two orthogonal polarized lights. Consequently, 4 bit information is transmitted at a single time slot in DP-QPSK modulation method.

*2 OIF (Optical Internetworking Forum): The industrial organization regarding optical communication.

*3 CFP / CFP2: The standard of the transceiver defined by MSA about 40 / 100 Gbit/s communication.

*4 CMRR (Common Mode Rejection Ratio): The value which indicates the capability of removing a common-mode signal.

*5 Mixer (Also known as 90˚ hybrid): In a coherent receiver, signal light and reference local oscillator light interfere with each other at a mixer. A mixer output interfered light for both in-phase and quadrature components.

*6 MMI: Multi-mode Interferometer

*7 Collimate light : Parallel light spread without being converged and spread.

*8 TIA (Transimpedance Amplifier): An amplifier which changes photodiode input current to output voltage.

*9 Skew: Phase difference (or delay) between channels.

*10 Constellation diagram: A figure which expresses the data signal point on a two-dimensional complex plane.

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