10 Channel, 45.6 Gb/s per Channel, Polarization-Multiplexed DQPSK, InP Receiver Photonic Integrated Circuit

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***Abstract*—We demonstrate a 10 wavelength, 200 GHz spaced, monolithically integrated, polarization-multiplexed, InP differential quadrature phase shift keying receiver operating at 45.6 Gb/s per wavelength. The receiver is based on a novel technique for polarization demodulation and phase tracking that does not require any external components.**

***Index Terms*—Monolithic InP integration, multichannel dense wavelength-division multiplexing receiver, photonic integrated circuit (PIC).**

I. Introduction

The first generation, 100 Gb/s (10 channel $\times$ 10 Gb/s per channel), InP large-scale photonic integrated circuits (PICs) we reported five years ago were based on the ON-OFF keying (OOK) modulation format [1]. A year later, using the same platform, we demonstrated a 40 channel OOK PIC, with each channel capable of operating at 40 Gb/s [2]. A more detailed description of these PICs, and a general account of the history of photonic integration on InP dating back to late 1960s may be found in [3].

OOK modulation format is spectrally not very efficient. Transmission formats employing phase modulation schemes are spectrally more efficient, and have been of much interest lately [4]. Two years ago, we reported a 10 channel, 40 Gb/s per channel, differential quadrature phase shift keying (DQPSK) transmitter PIC [5]. Recently using the same platform, we have demonstrated a 10 channel, 40 Gb/s per channel, polarization multiplexed (PM), return to zero DQPSK transmitter PIC [6].

In general, optical phase modulated formats require a phase reference in the form of a laser local oscillator (LO) for demodulation. On the other hand, DQPSK signals that use differential phase coding can be demodulated using a delay line interferometer [4]. In addition, PM systems typically used to double the spectral efficiency, require real-time polarization tracking and demodulation. In coherent detection systems using a local oscillator this can be done in real time using digital signal processing algorithms [7]. In the early demonstrations of non-LO-based PM DQPSK systems, the incoming signal was polarization demultiplexed "manually" using a polarization controller followed by a polarization beam splitter (PBS) [8], [9]. Recently, methods for automatic polarization tracking using external active optics have been reported [10], [11]. In a modified version of the PM DQPSK format reported recently, the signal is time/polarization multiplexed, with half-symbol time interleaving, at the transmitter, and then detected using decision circuitry operating at *twice* the symbol rate without the need for explicit optical polarization demultiplexing [12].

In this paper, we report a 10 channel, 45.6 Gb/s per channel, PM DQPSK InP receiver PIC. This PIC is based on a novel demodulation technique for PM DQPSK signals that uses multiple combinations of the optical input signal to decode the data irrespective of polarization alignment at the receiver [13], [14]. Rahn *et al.* [13] describe a Si planar lightwave circuit/InP photodiode hybrid implementation of the receiver. Here, we describe a complete PM DQPSK receiver using a monolithically integrated InP PIC first reported in [14].

II. DQPSK PIC Architecture

A. Device Layout

Fig. 1 shows the architecture of the DQPSK received PIC. At the PIC input is the polarization processing block that is common to all ten wavelengths. The input signal is first split into its TE and TM components using a PBS. The TM output of the PBS then passes through a polarization rotator that converts the signal to the TE polarization (labeled TE*). The adjacent arm with the original TE component has a variable optical attenuator (VOA) to compensate for the insertion loss of the rotator, and power balance the two outputs of the polarization processing block. The TE and TE* signals are then wavelength demultiplexed using a single array waveguide grating (AWG).

The demultiplexed outputs of the AWG are then fed to the network composed of 1-bit delay interferometers, and 90° optical hybrids. The circuit combination is repeated for each demultiplexed wavelength channel. In a conventional DQPSK decoder the TE and TM components would be separately processed by

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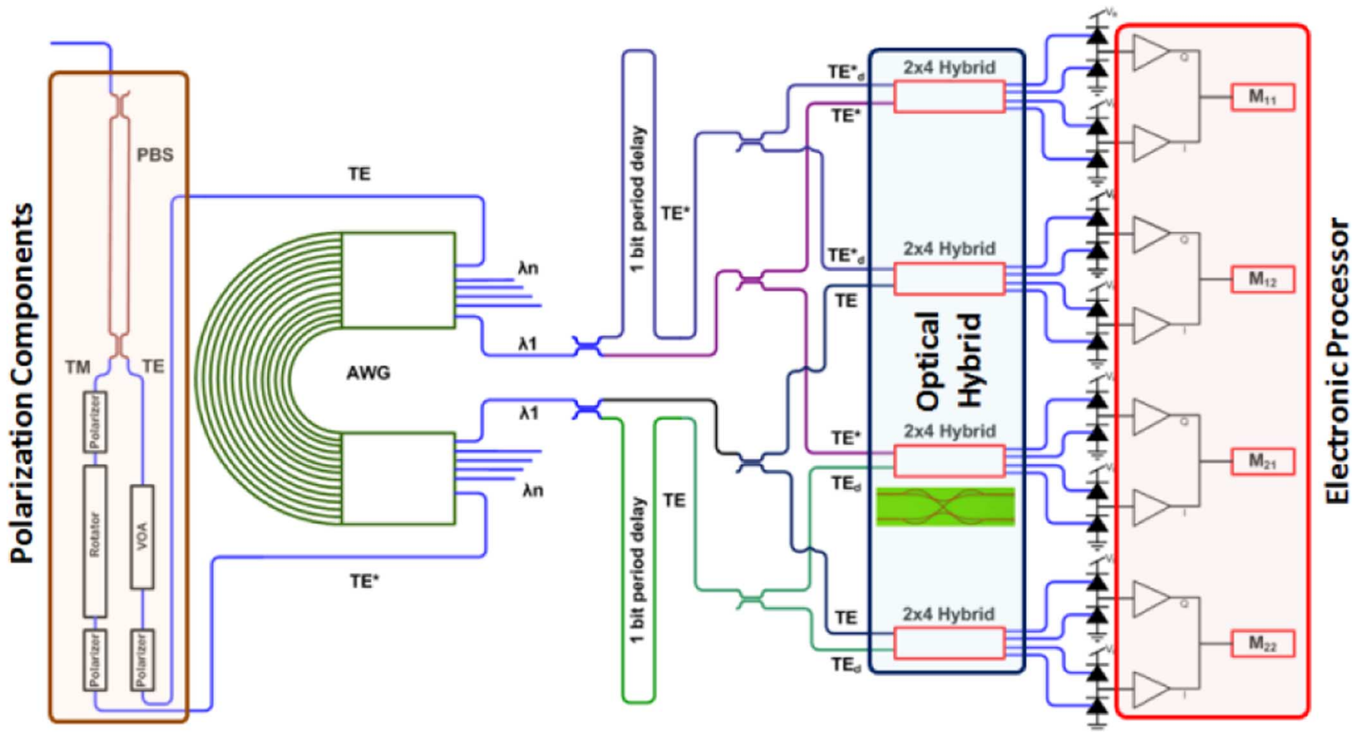

Fig. 1. DQPSK receiver PIC architecture.

mixing the original signal with its delayed component (TE_d). In this architecture, we create the following four combinations, $\mathrm{TE}+\mathrm{TE}_d, \mathrm{TE}^*+\mathrm{TE}_d, \mathrm{TE}+\mathrm{TE}^*{}_d$, and $\mathrm{TE}^*+\mathrm{TE}^*{}_d$. Since they are orthogonal, combinations of TE and TM signals would not produce any signal output. The polarization rotator at the input that converts the TM to the TE makes this architecture possible.

The four outputs of the optical hybrid are terminated in two pairs of balanced high speed photodetectors (PD). The two inputs to a balanced PD pair are 180° out of phase, and create a differential signal output. Further, the two PD pairs have a 90° phase offset between them, and this phase offset is used to separate the I (in-phase) and Q (quadrature) components of the quadrature phase modulated signal.

The PD outputs are then fed to a copackaged electronic processor ASIC. This ASIC has high-speed transimpedance amplifiers (TIAs), one per PD pair, as the input stage. There are 16 PDs per channel (wavelength) for a total of 160 PDs on the PIC. It is almost impossible to build such a receiver reliably out of discrete components, and it is in realizing architectures like these that monolithic photonic integration triumphs.

B. Polarization Tracking

This section describes the mathematical foundation for the PM-DQPSK demodulation, in particular the signal processing that enables polarization tracking

$$\begin{aligned}D_{\mathrm{out}} &= \mathrm{PD}_1 - \mathrm{PD}_2 + j\mathrm{PD}_3 - jPD_4\\ &= |E_{k-1}+E_k|^2 - |E_{k-1}-E_k|^2\\ &\quad + j|E_{k-1}+jE_k|^2 - j|E_{k-1}-jE_k|^2\\ &= (|E_{k-1}|^2 + 2\mathrm{Re}[E_{k-1}^*E_k] + |E_k|^2)\\ &\quad - (|E_{k-1}|^2 - 2\mathrm{Re}[E_{k-1}^*E_k] + |E_k|^2)\\ &\quad + j(|E_{k-1}|^2 + 2\mathrm{Im}[E_{k-1}^*E_k] + |E_k|^2)\\ &\quad - j(|E_{k-1}|^2 - 2\mathrm{Im}[E_{k-1}^*E_k] + |E_k|^2)\\ &= 4E_{k-1}^*E_k. \end{aligned} \tag{1}$$

The purpose of the two balanced receivers, mixing the bit-delayed and current optical signals, is to extract electrically the difference in phase between two sequential bits. Equation (1) demonstrates how the electrical outputs can represent the complex phase between the two signals. Practically, the two electrical signals carry the in-phase and quadrature portions of the phase on two distinct wires. It is convenient to represent the two signals mathematically as one complex value.

For phase modulated formats, the electrical field at the transmitter is $E_k = e^{j\alpha_k}$, representing the electric field in the optical domain. In order to extract the phase change between two sequential bits in pol-muxed DQPSK, the circuit in can be represented mathematically using (2) and (3). In this case, the two orthogonal polarization states generated at the transmitter are shown as having arrived at the receiver without any rotations. The matrix represents an ideal polarization splitter, which yields two (complex) electrical outputs representing the phase change for horizontal and vertical polarizations

$$\begin{bmatrix} e^{-i\alpha_{k+1}} & e^{-i\beta_{k+1}} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e^{i\alpha_k} \\ e^{i\beta_k} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} e^{-i\alpha_{k+1}} & e^{-i\beta_{k+1}} \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} e^{i\alpha_k} \\ e^{i\beta_k} \end{bmatrix}. \tag{3}$$

The polarization rotation through a lossless fiber can be represented by the Jones matrix shown as follows:

$$R = \begin{bmatrix} e^{i\phi}\cos\theta & -e^{-i\psi}\sin\theta \\ e^{i\psi}\sin\theta & e^{-i}\cos\theta \end{bmatrix}. \quad (4)$$

For light transmitted through an arbitrary polarization rotation, the corresponding signals seen electrically can be described using the following equations:

$$\begin{bmatrix} e^{-i\alpha_{k+1}} & e^{-i\beta_{k+1}} \end{bmatrix} R^{-1} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R \begin{bmatrix} e^{i\alpha_k} \\ e^{i\beta_k} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} e^{i\alpha_{k+1}} & e^{i\beta k+1} \end{bmatrix} R^{-1} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} R \begin{bmatrix} e^{i\alpha_k} \\ e^{i\beta_k} \end{bmatrix}. \quad (6)$$

Expanding the $\mathrm{R}^{-1}\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}\mathrm{R}$ matrix by itself yields (7) and (10). A conventional technique for receiving pol-mux DQPSK signals would be to place an optical polarization tracker before the optical receiver. However, a real-time polarization tracker is difficult to realize in optics. If the TE and TM signals are also mixed together (using a 90° polarization rotation on one of the polarization states), additional information is obtained about the incoming data stream. While additional photodiodes are required, this enables polarization tracking of the data sequence through signal processing. For simplicity, the Jones matrix angles are simplified with the notation $c = \cos 2\theta$ and $s = \sin 2\theta$

$$R^{-1}\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R = \frac{1}{2}\begin{bmatrix} 1+c & -se^{-i\phi-i\psi} \\ -se^{i\phi+i\psi} & 1+c \end{bmatrix} \quad (7)$$

$$R^{-1}\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} R = \frac{1}{2}\begin{bmatrix} se^{-i\phi+i\psi} & (1+c)e^{-2i\phi} \\ -(1-c)e^{2i\psi} & -se^{-i\phi+i\psi} \end{bmatrix} \quad (8)$$

$$R^{-1}\begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} R = \frac{1}{2}\begin{bmatrix} se^{i\phi-i\psi} & -(1-c)e^{-2i\psi} \\ (1+c)e^{2i\phi} & -se^{i\phi-i\psi} \end{bmatrix} \quad (9)$$

$$R^{-1}\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} R = \frac{1}{2}\begin{bmatrix} 1+c & se^{-i\phi-i\psi} \\ se^{i\phi+i\psi} & 1-c \end{bmatrix}. \quad (10)$$

In order to demonstrate that the data are sufficient for demodulating the incoming streams electrically without regard to the polarization state, the 16 values shown in (7)–(10) are rearranged into a 4×4 matrix M, given by (11), shown at the bottom of the page.

M is nonsingular, which is required for polarization tracking, and its inverse is given by (12), shown at the bottom of the page.

M^{-1} represents the coefficients that weigh the outputs from the eight differential TIA outputs to generate the eight mixtures of (7)–(10). However, only the mixing of the bits within the same polarization is of importance. This is represented by the first and last row of M^{-1}, rewritten as S in the following equation:

$$S = \frac{1}{2}\begin{bmatrix} 1+c & se^{i\phi-i\psi} & se^{-i\phi+i\psi} & 1-c \\ 1-c & -se^{i\phi-i\psi} & -se^{-i\phi+i\psi} & 1+c \end{bmatrix}. \quad (13)$$

In order to realize this receiver, a multiple-input, multiple-output signal processing structure is needed that can make linear combinations of the input signals to produce a single output signal.

Fig. 2 shows a schematic representation of this approach for four possible states of polarization at the input. For the case where the transmit polarization aligns with the polarization splitter at the receiver, polarization demultiplexing appears reasonably conventional with the splitter separating the two polarizations and a bit-delay interferometer performing the DQPSK demultiplexing. In Fig. 2(a), the highlighted waveguides show one of the four data streams' paths. The demultiplexed signal comes from a single balanced photodiode pair, as shown by the arrow. In Fig. 2(b), a 90° rotation occurs and the same data stream ends up on a different set of photodiodes. In Fig. 2(c), the polarization is circularly polarized such that the signal must be reconstructed from four independent photodiodes, as shown by the arrows. For a linear polarization at 45° from the transmit [see Fig. 2(d)], a similar combination restores the original datastream; only the contribution from the polarization mixed components needs to change.

The signal processing can be performed in either analog or digital domain. Moreover, adaptation of the receiver can be achieved using conventional least mean squares (LMS) adaptation. By employing a signal-processing-based adaptation, rapid polarization transients can be tracked as optical response time does not limit tracking capability [13].

A benefit of the LMS adaptation is that crosstalk occurring between the outputs is always minimized. Variation in the response of photodiode pairs will be tracked by the gain cells

$$M = \frac{1}{2}\begin{bmatrix} 1+c & -se^{-i\phi-i\psi} & -se^{i\phi+i\psi}s & 1-c \\ se^{-i\phi+i\psi} & (1+c)e^{-2i\phi} & -(1-c)e^{2i\psi} & -se^{-i\phi+i\psi} \\ se^{i\phi-i\psi} & -(1-c)e^{-2i\psi} & (1+c)e^{2i\phi} & -se^{i\phi-i\psi} \\ 1-c & se^{-i\phi-i\psi}s & se^{i\phi+i\psi}s & 1+c \end{bmatrix} \quad (11)$$

$$M^{-1} = \frac{1}{2}\begin{bmatrix} 1+c & se^{i\phi-i\psi} & se^{-i\phi+i\psi} & 1-c \\ -se^{i\phi+i\psi} & (1+c)e^{2i\phi} & -(1-c)e^{2i\psi} & se^{i\phi+i\psi} \\ -se^{-i\phi-i\psi} & -(1-c)e^{-2i\psi} & (1+c)e^{-2i\phi} & se^{-i\phi-i\psi} \\ 1-c & -se^{i\phi-i\psi} & -se^{-i\phi+i\psi} & 1+c \end{bmatrix} \quad (12)$$

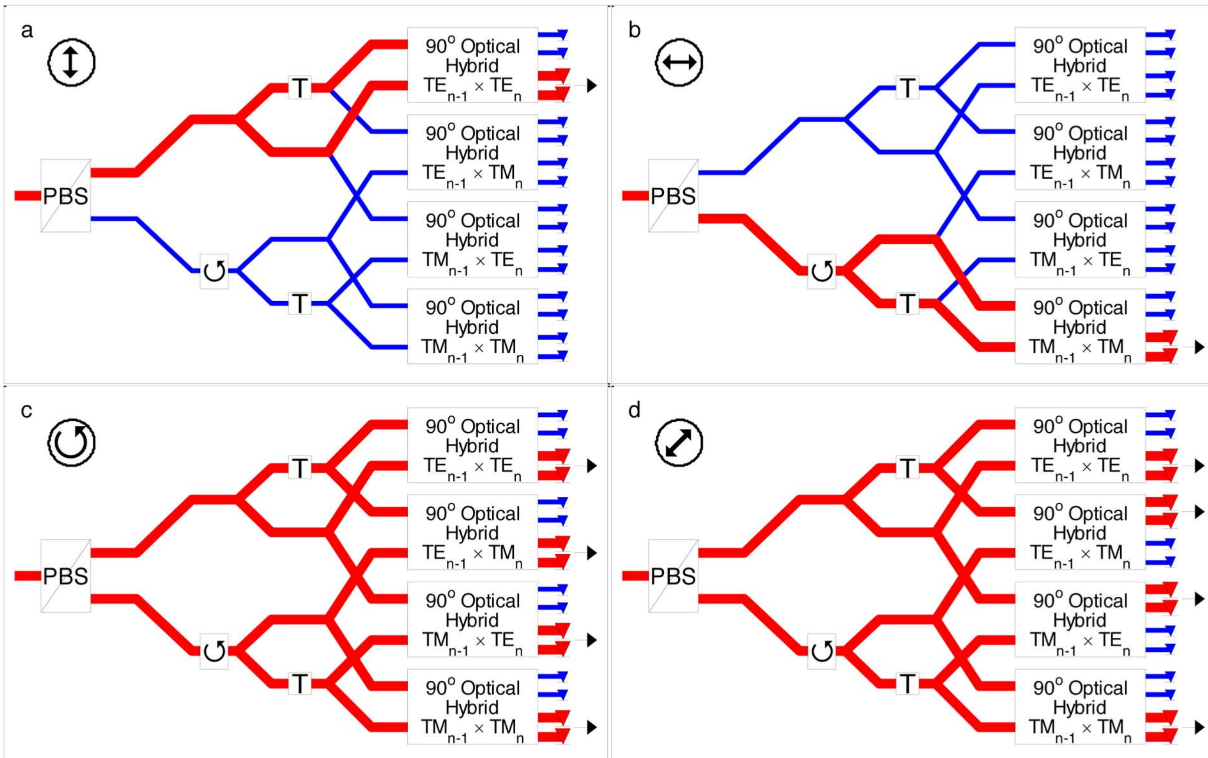

Fig. 2. Signal paths required to reconstruct four example states of polarization.

without any intervention. DQPSK has excellent phase noise tolerance, such as to cross-phase modulation often present in wavelength-division multiplexing systems. To first order, sensitivity to chromatic and polarization dispersion depends on the baud rate. Chromatic dispersion needs to be compensated within a window that is similar to other 10 GBaud modulation formats, such as single-polarization DQPSK. Simulation and experiment have not shown any particular sensitivity that the tracking introduces to chromatic dispersion tolerance.

III. DQPSK PIC PERFORMANCE

A. Polarization Components

Optical power splitters and combiners, connected in various ways, are at the heart of this PIC layout. These are typically built either as directional couplers (DC) [15] or multimode interference (MMI) [16] couplers. DC require very good fabrication control of the width of the gap between the coupler waveguides. On the other hand, for acceptable performance, MMI couplers require very good control of the dimensions of the multimode section. We chose to go with the MMI-based architecture for the PIC.

Fig. 3 shows the polarization extinction ratio (PER) performance of the PBS at the input of the PIC. The PBS is based on an asymmetric Mach Zehnder interferometer (MZI) structure [17]. PBS devices based on DC geometries have also been successfully demonstrated [18].

In the MMI-based PBS structure, the TM mode index is preferentially changed in one of the arms of the MZI. When we induce a π-phase change preferentially for the TM polarization, we get the response shown in Fig. 3. The PER is measured between the TM cross and TE cross or between TM bar and TE bar states. We have better than 20 dB PER.

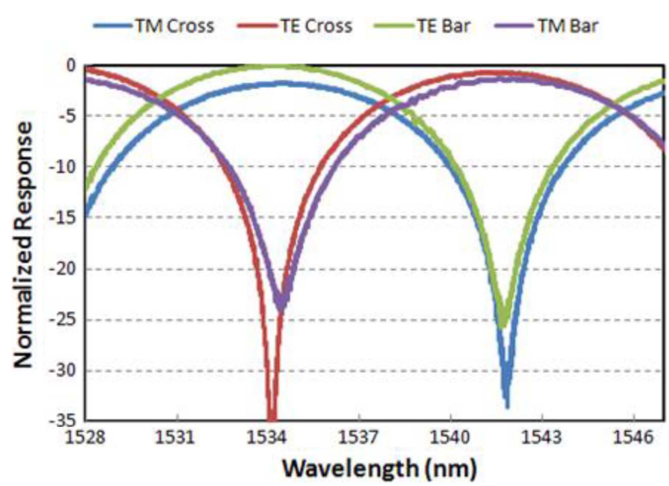

Fig. 3. Performance of a PBS test structure over wavelength. The PBS FSR of 16 nm is due to the deliberate design of the MZI test structure used to measure the PER.

The wavelength response of the PBS is very flat over a large wavelength range. The free spectral range (FSR) of 16 nm in the stand-alone MZI test structure, shown in Fig. 3, is due to the deliberate design modification that was used to characterize the PER. In the integrated PBS device, the path lengths of the MZI arms are matched for performance over a wide wavelength range.

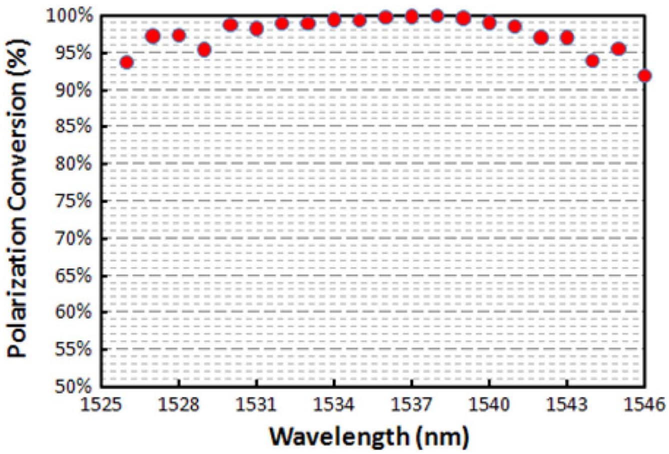

Fig. 4. Performance of the polarization rotator with wavelength.

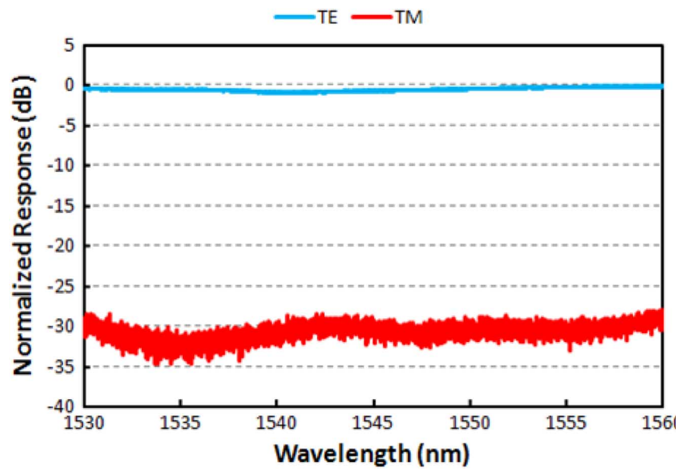

Fig. 5. TE polarizer performance over wavelength shows a better than 25 dB extinction ratio.

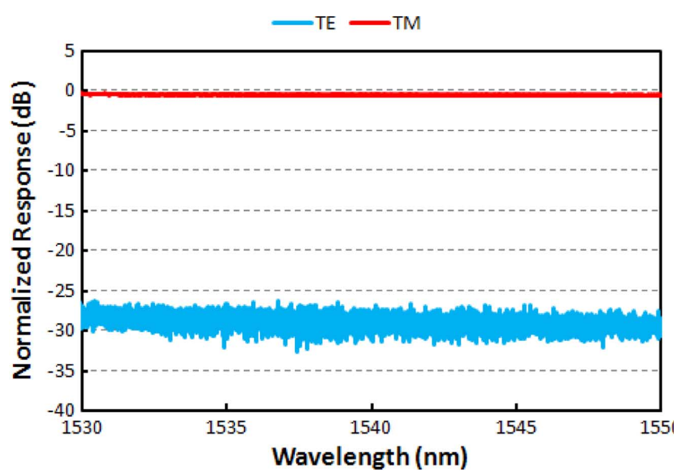

Fig. 6. TM polarizer performance over wavelength also shows a better than 25 dB extinction ratio.

The TE and TM outputs of the PBS have orthogonal electric field orientations. The rotator is used to convert the TM output (which is oriented perpendicular to the plane of the substrate) to the same orientation as the TE output (which is oriented parallel to the plane of the substrate). Even symmetric optical waveguides have some birefringence in general, i.e., they have different propagation constants for the TE and TM modes. A beat length refers to the propagation distance in the waveguide over which a π-phase difference accumulates between the TE and TM modes. Cross-sectional asymmetries or compositional variations may be used to increase the birefringence in waveguides, and shorten the beat length.

Polarization rotators are commonly made of asymmetric waveguides, e.g., waveguides with one sloped sidewall and one vertical sidewall [19]–[21]. The waveguide design is such that the eigenmodes of the structure is oriented at an angle of 45° to the TE/TM eigenmodes of the input and output waveguides with vertical sidewalls. After propagating a beat length inside the rotator, the electric field of the input optical mode is effectively "rotated" to its orthogonal orientation. A rotator built from this principle is a periodic structure and has to be terminated at its beat length. Otherwise, the input optical field will continue to evolve inside the rotator. Rotators may also be built out of waveguides with trenches [22], [23] or tight optical bends [24], [25] to provide the required asymmetry.

We used an asymmetric waveguide design similar to [21] for the rotator. Fig. 4 shows performance of the polarization rotator. In the wavelength range shown, the TM/TE conversion is well over 90%, typically in excess of 20 dB extinction of the unwanted polarization. The insertion loss is less than 0.5 dB.

We used an electrical heater tuned MZI design for the VOA in the TE path. The VOA was used to compensate for the losses in the TM path, and power balance the two signal paths.

A TE polarizer is a device with high insertion loss for the TM polarization, and operates with minimal insertion loss for the TE polarization. The TM polarizer does the opposite. There is a TM polarizer at the TM output of the PBS just before the rotator. Although the PBS has a PER in excess of 25 dB, the TM polarizer further cleans up the signal path by stripping away any residual TE signal. There is a TE polarizer after the rotator in the TM path and after the VOA in the TE path. This ensures that any residual TM signal (capable of causing coherent crosstalk) has been completely eliminated from the signal paths. Polarizers are metal clad waveguides that preferentially affect the TE or TM signal states.

Fig. 5 shows the performance of the TE polarizer and Fig. 6 shows the performance of the TM polarizer as a function of wavelength. They both have PER in excess of 25 dB over a wide wavelength range.

B. Wavelength Demultiplexer and Optical Hybrid

Fig. 7 shows the optical spectrum of the AWG used as the wavelength demultiplexer [26], [27]. The design is similar to the ones that we have used on our OOK PICs [3]. The AWG insertion loss is of the order of 2.5 dB and the adjacent channel crosstalk is better than 25 dB.

Fig. 8 shows the performance of a stand-alone 2×4 optical hybrid with extinction ratio in excess of 20 dB. The optical hybrid, required to create the 90° phase offset between the I and Q components of the DQPSK signal, may be built from a series of 2×2 MMIs (as shown as an inset in Fig. 1), a single 2×4 MMI [28], [29] or series of DC [13]. In the 2×4 (or generally a 4×4) MMI the 90° IQ phase offset is the result of the physical

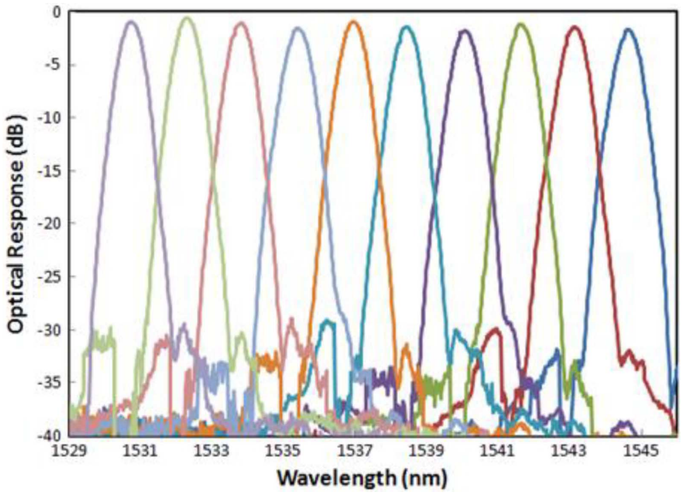

Fig. 7. 10 Channel, 200 GHz spaced AWG performance.

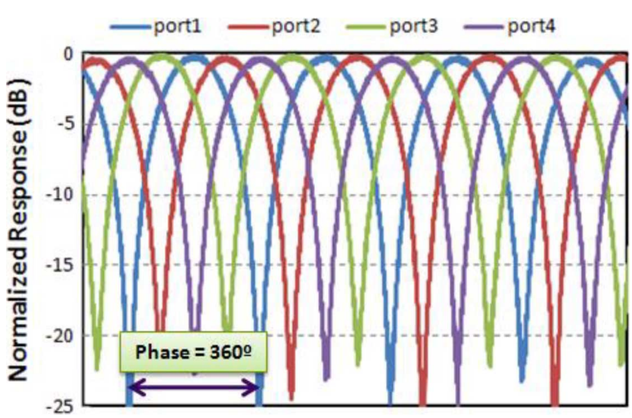

Fig. 8. Performance of stand-alone optical hybrid test structure.

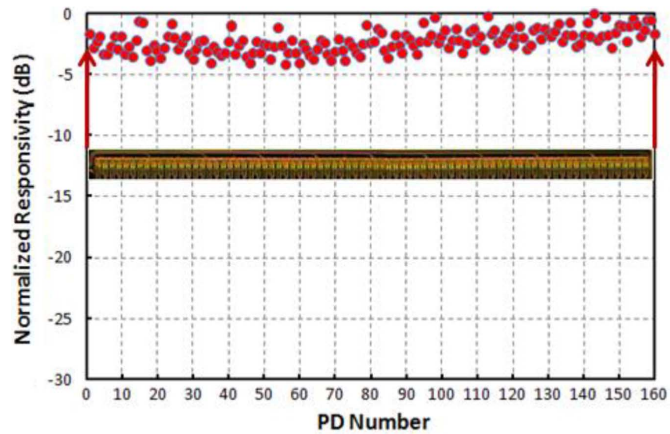

Fig. 9. Normalized DC responsivity of the 160 PD array (shown as the inset) across the PIC.

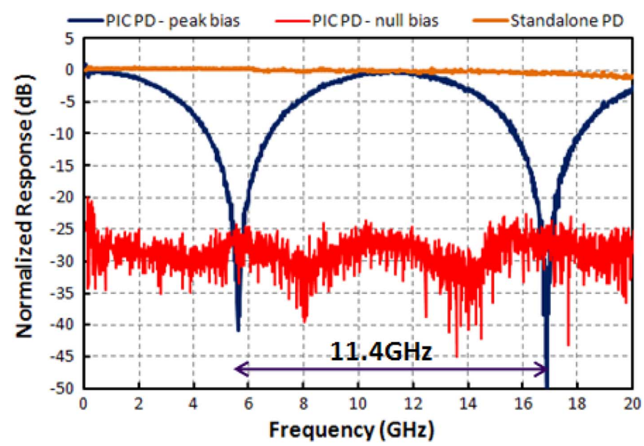

Fig. 10. S21 response of a stand-alone PD compared to one with the optical hybrid ahead of it. The red curve is the result of the optical hybrid being biased at a null.

phase relationships between four outputs of the MMI structure. In the other two cases, the waveguide layout needs to be strictly controlled to achieve the required phase offset. In our case, 90° phase offset of the optical hybrid is not actively controlled.

The FSR of the 1-bit delay is designed to match the baud rate of the DQPSK signal that is 11.4 Gb/s. The AWG channel spacing is 200 GHz. In the integrated version, multiple 1-bit delay passbands would fit inside of one AWG passband.

Fig. 9 shows the normalized responsivity of the array of 160 PDs. The responsivity measurement is done using a tunable laser source (TLS) first aligned to the TE and then to the TM orientation on PIC. Wavelength sweep of the TLS produces a series of fringes at the PDs (the composite response is a product of responses in Figs. 7 and 8). Reported responsivity is the peak value of the composite response at the PD. The total power variation across all channels is within 4 dB. This variation has contributions from all the components up to and including the PDs. The insertion loss performance of the devices is sufficient for implementation in a long haul network [the overall insertion loss of the receiver is not an issue in a network using erbium-doped fiber amplifiers (EDFAs)]. We can use the VOA, in the TE arm at the input, to achieve power balance between the two input polarizations. Further, the VOA may be adjusted over the life of the receiver to compensate for any changes in insertion loss between the TE and TM paths. The PD array is also shown in the figure.

C. RF Performance

Fig. 10 shows the S21 response (bandwidth) of the PD. The response of the stand-alone PD (in a separate test cell) drops only by about 1 dB at 20 GHz. When the response is measured on the PIC, the result is the characteristic filter response of the 1-bit delay. For this measurement, the 1-bit delay is biased at the peak of the passband. As also shown in Fig. 10, the filter response is suppressed at the null bias point. The electrically measured FSR of the 1-bit delay, 11.4 GHz, is in agreement with the optical measurement.

The PIC and the electronic processor (ASIC) are integrated into a ceramic multilayer package. The multilayer design allows complex internal signal and power routings while maintaining good RF signal integrity, without the need for separate thin film circuits and additional interconnects. The package has an electrical interface providing >1000 I/O connections for >450 Gb/s data, power and controls. A lensed fiber couples the input optical signal to the PIC waveguide and a thermoelectric cooler (TEC) maintains constant device temperature, and the package is hermetically sealed.

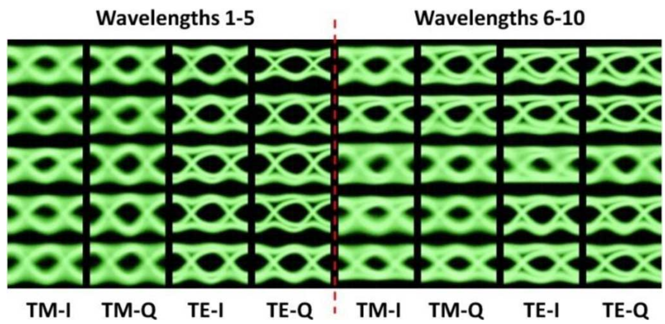

Fig. 11. Forty 11.4 Gb/s eye diagrams comprising of the I and Q data for both TE and TM polarizations from a package receiver.

Fig. 11 shows the forty 11.4 Gb/s eye diagrams of the demodulated DQPSK signal. The bit error rate performance of all the channels is well below the FEC-correctable limit. Most of the channels were error-free for the duration of the test. Thus, the package is capable of a total data rate of 456 Gb/s. Visually, some of the eye diagrams may look better than others. This is mostly due to variations in loss between the individual paths. The module was tested with the TEC nonoperational, i.e., without strict temperature control. This is possible because the resulting phase variation in the 1-bit delay was automatically tracked by the electronics.

IV. Summary

We have demonstrated a fully integrated PIC on InP that is capable of detecting and demodulating ten independent wavelength channels of PM-DQPSK signal. The polarization and phase tracking are accomplished using different combinations of the input signal and its 1-bit delayed version, and an electronic processor to implement the decoding algorithm. Unlike previous implementations, we do not need external optics or LO-based coherent techniques for polarization tracking and signal demodulation at the receiver.

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