# 1 Tbps on-Chip Multi-dimensional Receiver

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***Abstract*—We have designed and experimentally demonstrated a 1Tbps on-chip silicon multi-dimensional hybrid receiver. The proposed receiver accommodates a total of 20 channels (4 modes and 5 wavelengths), and each of them supports 50 Gbps On-Off Keying (OOK) signal transmission.**

***Keywords—Silicon; Integrated photonics; Hybrid Multiplexing; Mode; Polarization; Wavelength; Photonic Detector.***

## I. INTRODUCTION

The rapidly increasing demand for high-capacity communication pushes the development of optical interconnection technology [1]-[4]. On-chip optical receiver architecture based on wavelength division multiplexing (WDM) technology is expected to achieve a high transmission rate[5]-[6]. However, due to the bandwidth limitations of erbium-doped fiber amplifiers (EDFA), as well as the requirement for channel bandwidth and spacing, The WDM technology can only provide a limited channel number[7]. The emerging module division multiplexing (MDM) and polarization division multiplexing (PDM) technology utilizes multiple modes as independent signal channels [8]-[10] and increases the channel number heavily, providing a new dimension for further increasing traffic capacity.

In this paper, we proposed and demonstrated a 20-channel silicon-on-insulator (SOI) hybrid MDM-WDM-PDM receiver containing 4 modes and 5 wavelengths. The fabricated hybrid receiver chip has on-chip excess losses (ELs) of 1-2 dB, and inter-mode crosstalk < -15 dB for each channel. The system experiments are demonstrated by using 50-GBaud On-Off Keying (OOK) signals and showing high-quality eye-diagram. The proposed scheme can be extended easily for even higher capacity by adopting more mode- or wavelength- channels.

## II. STRUCTURE AND DESIGN

As shown in Fig. 1 (a), the proposed multi-dimensional receiver consists of a 4-channel hybrid MDM-PDM de-multiplexer(DE-MUX), a 4 × 5 array of MRR-based wavelength-selective switches, and 20 photodetectors. The 4-channel hybrid MDM-PDM DE-MUX is designed for three transverse electric (TE) modes (i.e., the $TE_0$, $TE_1$ and $TE_2$ modes) and a fundamental transverse magnetic ($TM_0$) mode. The resonant wavelengths of 5 cascaded microring resonators (MRRs) increase from 1541.3 nm to 1554.1 nm with a channel spacing of 3.2 nm. Moreover, the bandwidth of 4 × 5 photodetectors ($PD_{n:m}$) displayed at the end of each channel is 50 GHz.

For the hybrid receiver, data propagating along the multimode bus waveguide (MBW) are carried by 4 mode- and 5 wavelength channels. When the data arrives at the input MBW of the receiver chip, they are first demultiplexed into four $TE_0$ modes by using the mode DEMUX together with the polarization rotators (PRs)/ polarization splitting rotator (PSR), and then pass through the four SMWs cascaded with 5 MRR switches, respectively. For each $TE_0$ mode propagating through the SMW, the 5 wavelength channels ($\lambda_1,\ldots,\lambda_5$) are dropped and detected by the $PD_{n:m}$ ($m$=1,...4, $n$=1,…,5) with the corresponding MRR switch. The integrated 4 × 5 PDs were employed to convert the high-speed optical signal into an electric signal.

## III. FABRICATION AND MEASUREMENT

The receiver chip was fabricated based on the typical active SOI foundry process (CompoundTek, Singapore). The cross-section of the passive silicon waveguide is shown in Fig. 1 (b), it has a 220-nm-thick top-silicon layer and a 2-μm-thick BOX layer. While for the active Ge-Si waveguide as shown in Fig. 1 (c), the bottom silicon waveguide was implanted with P-type light doping concentration first, then a high doping concentration was implanted to form ohmic Si contact. The 500nm-thick tensile-stressed Ge film was selectively grown on a 220nm-thick silicon waveguide, the width and length of the epitaxial Ge film are 4um and 20um respectively to achieve high responsivity and high bandwidth. Finally, the Ge film was N-type highly doped to form ohmic Ge contact. Fig.2 shows the microscopy images for the fabricated multi-dimensional receiver chip. An additional MUX is connected with the input port of the receiver chip thus selectively exciting the needed modes for measurement. The TM-type and TE-type grating couplers are used for the fiber-chip coupling.

The transmission spectra of the fabricated hybrid receiver for the dropsignal are measured first. Here, we measured a test structure that is identical to the original receiving array structure, except for replacing the PD port $PD_{1\text{-}5:j}$ ($j$=1-4, corresponding to the $TM_0$, $TE_0$, $TE_1$ and $TE_2$ mode channels) with a vertically coupled grating.Light from a broadband source is launched into the input ports $I_i$ ($i$=1-4, corresponding to the $TM_0$, $TE_0$, $TE_1$ and $TE_2$ mode channels) with a single-mode fiber (SMF). And the light

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output from the chip PD ports $PD_{1\text{-}5:j}$ ($j$=1-4) is then received with another SMF and sent into an optical spectrum analyzer (OSA). It is worth mentioning that the central wavelength of MRR in receiver system is stable enough to align the corresponding wavelength channel without thermal adjustment, which greatly reduces power consumption. Fig. 3(a-d) shows the measured transmission $T_{ij}$ from port $I_i$ to port $PD_{1\text{-}5:j}$ for i=1, 2, 3 and 4, respectively. Here the transmission is normalized with respect to that of a straight waveguide fabricated on the same chip. The transmission $T_{ij}$ is mainly dependent on the performance of the pairs of mode/polarization (de) MUXs and DE-MUX and the through response of each 5 cascaded MRR array. It shows that the receiver chip has an on-chip EL of 1-2 dB and inter-mode crosstalk < -12 dB for four mode channels. The dips at the transmission spectra are aroused by the drop operation of the MRR-based switches.

We further characterized the system high-speed transmission performances of the present on-chip hybrid receiver for the drop signal, where 50-GBaud On-Off Keying (OOK) signals are used and the high-quality eye patterns for 20 channels are shown in Fig. 4. The bandwidth of MRR switches is designed to be >1 nm with a channel spacing of 3.2 nm. For the receiver, all channels can meet the transmission rate of 50 Gbps, making the entire receiver system meet the communication capacity of 1Tbps. It should be mentioned, that the baud rate of the system is limited by the narrow bandwidth of the MRR switches. A higher-order MRR with a box-like response will increase the optical link traffic capacity.

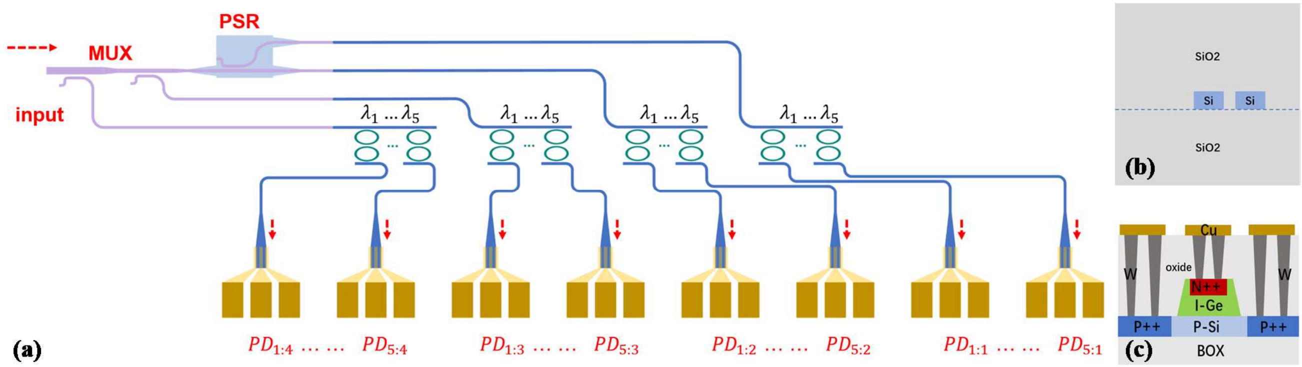


Fig. 1: (a)Schematic configuration of the proposed receiver chip for the hybrid MDM-PDM-WDM systems. (b) The Cross-section of the passive silicion waveguide. (c) The cross-section of the Ge/Si photodetector.

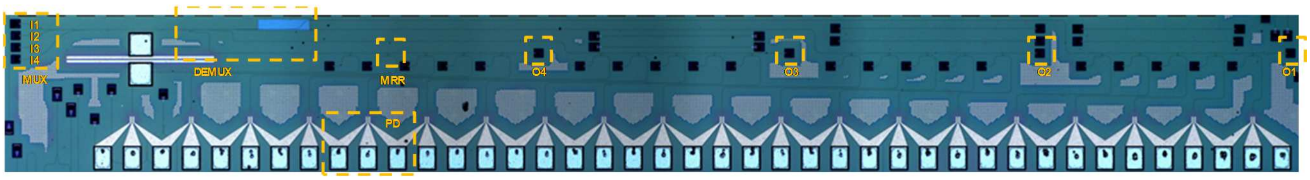


Fig.2: Microscopy image of the fabricated receiver chip for the hybrid MDM-PDM-WDM systems.

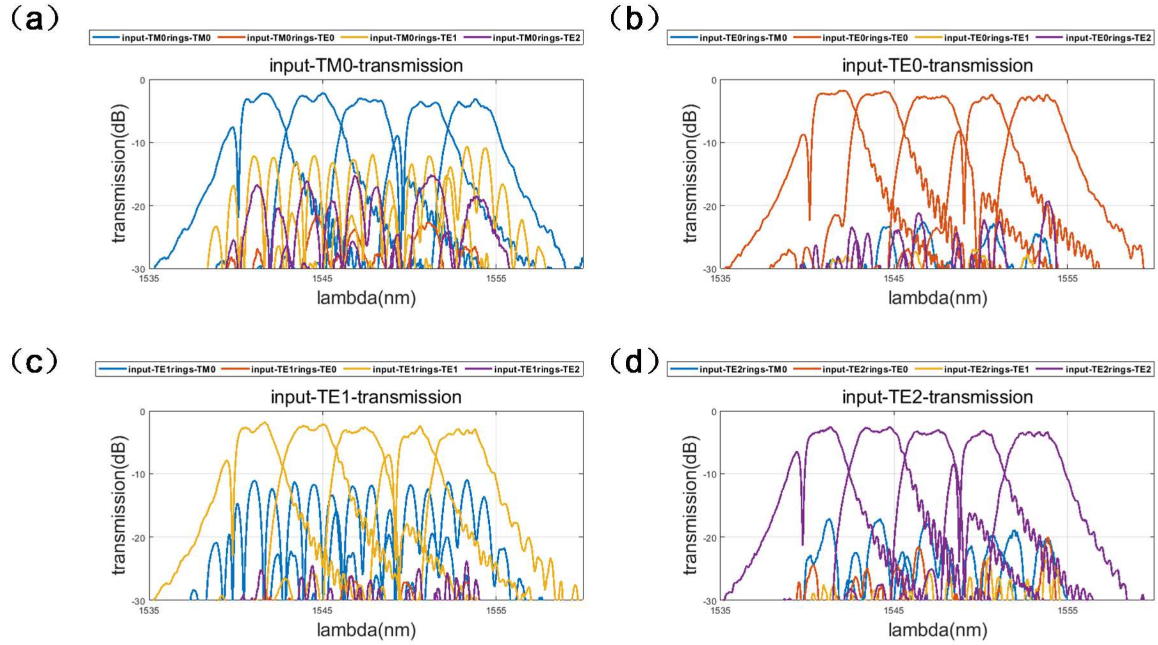


Fig.3: Meausred drop transmission of test structure for multi-dimenional receiver chip at $PD_{1\text{-}5:1}$-$PD_{1\text{-}5:4}$ Ports when light input from (a) $I_1$ (b) $I_2$, (c) $I_3$ (d) $I_4$.

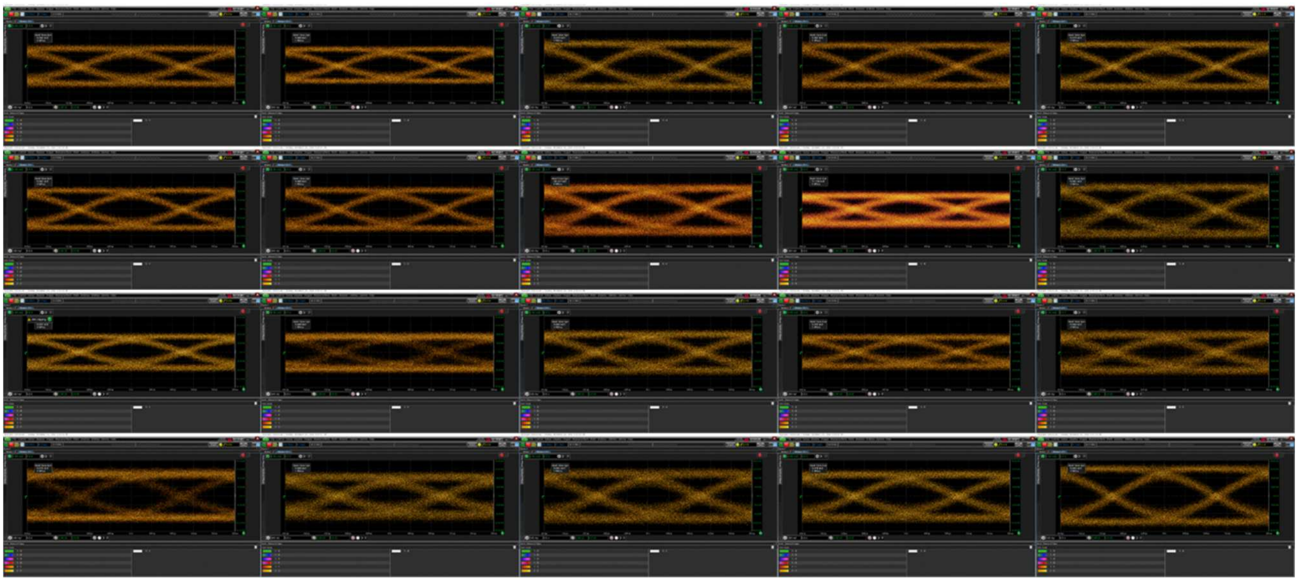

Fig.4: Eye pattern of 50-GBaud OOK transmission for 20 channels in the hybrid MDM-PDM-WDM systems.

## IV. Conclusion

In summary, we have designed and demonstrated a 1-Tbps silicon receiver for hybrid MDM-WDM-PDM systems. This hybrid receiver consists of a four-channel mode de multiplexers, a 4 × 5 array of MRR-based wavelength-selective switches, and 4 × 5 photodetectors. The hybrid receiver shows on-chip ELs of 1–2 dB, and inter-mode crosstalk < -15 dB for four mode channels in the wavelength range of 1541–1554 nm. The system experiments have been demonstrated by using 50-GBaud OOK signals. The performance of the proposed hybrid receiver can be further improved by adopting low crosstalk mode (DE)MUX. Such a multi-dimensional receiver can be extended easily by adopting more mode or wavelength channels and can find applications in future optical interconnect networks.

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