Full-Duplex Analog Radio-over-Fiber System based on an Integrated Transceiver with a Silicon Microring Modulator and a Transfer-Printed III-V Photodetector

Student Paper

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ABSTRACT

A full-duplex analog radio-over-fiber (RoF) system based on an integrated transceiver is proposed. The transceiver incorporates a C-band silicon microring modulator for the electrical-to-optical (E-O) conversion of the downstream signal and an O-band III-V photodetector (PD) is transfer printed onto the same chip for the optical-to-electrical (O-E) conversion of the upstream signal. With the integrated transceiver, a proof-of-concept experiment is carried out. An error vector magnitude (EVM) less than 6 % is achieved in the X-band for a 1-Gbps 16QAM-modulated signal transmitted through 5-km single mode fiber.

Keywords: radio transceivers, microwave photonics, silicon photonics, photodetector.

1. INTRODUCTION

It is well known that next-generation wireless communication systems, 5G for example, have stringent requirements in terms of massive device connectivity, high capacity, large coverage, low latency and sustainable cost. Cloud radio access networks (CRANs) are regarded a key technical enabler, since all the remote radio heads (RRHs) are connected to a baseband unit (BBU) “pool” in the central office (CO) via optical fiber [1]. Thanks to this centralized architecture, the resources in the CO can be shared according to the traffic requirements, and it also enables co-operative radio technologies to reduce the interference between the different RRHs, allowing a further increase in their density. Obviously, to ensure a connection of a large number of cells, the cost, complexity and power consumption of the RRH is expected to be as low as possible. Analog radio-over-fiber (RoF) technology, due to its simple RRH structure, is considered one of the most convincing solutions [2]. In the analog RoF link, the signal is directly upconverted to an analog signal at the carrier frequency and transmitted to the RRH via optical fiber, so no digital-to-analog (DAC) converter and frequency conversion are needed in the RRH. In recent years, various systems based on an analog RoF architecture have been reported, focusing mainly on pushing the carrier frequency to high frequency bands (millimetre-wave [3] or even THz [4] band) or combining RoF with other techniques, such as massive MIMO [5] and coordinated multipoint (CoMP) [6], to improve the capacity and spectral efficiency.

In this paper, we propose an integrated silicon photonic transceiver for a full-duplex analog RoF system. Silicon photonics offers compatibility with the mature CMOS technology and enables low cost transceiver manufacturing in high volume, which is very attractive for the wireless communications of the future. In the proposed transceiver, a C-band silicon microring modulator is integrated to realize electrical-to-optical (E-O) conversion for the downstream link, and an O-band III-V photodetector (PD) for the upstream link is integrated onto the same chip via transfer printing technology for the optical-to-electrical (O-E) conversion. Since the transfer-printed PD is ‘transparent’ for the C-band downstream signal, the III-V PD is directly placed onto the grating coupler without affecting the downstream signal, which reduces the footprint of the transceiver and also enables the duplexing of C-band and O-band signals in the same optical fiber. With the integrated transceiver, a proof-of-concept experiment is carried out. An error vector magnitude (EVM) less than 6% is achieved in the X-band for a full-duplex 1-Gbps 16QAM-modulated signal transmitted through 5-km single mode fiber.

2. DEVICE AND SYSTEM

Fig. 1(a) shows the microscope image and schematic cross-section of the proposed integrated transceiver. The silicon photonic circuit, which consists of two grating couplers for the in/out coupling of light and a C-band microring modulator for the downstream modulation, is realized in imec’s iSIPP25G platform. The insertion loss of each grating coupler is about 4 dB. The free spectral range (FSR) of the microring modulator is about 12.72 nm and the 3-dB RF bandwidth at −1 V bias is about 15 GHz. To realize a full-duplex communication, a PD is required for the photodetection of the upstream signal. The integration of the PD to the silicon photonic wafer is realized by a technology called transfer printing [7]. Transfer printing, with a schematic flow shown in Fig. 1(b), is regarded as a promising solution for massively parallel integration of III-V components to another substrate, which leads to a significant improvement in material use and throughput compared to conventional wafer bonding and flip-chip-like assembly methods. In this paper, the PD to be transfer printed is designed to consist of a 1 μm thick intrinsic InGaAsP absorbing layer with a cut-off wavelength of 1.37 μm (i.e., O-band), which is 'printed' on the grating coupler to make the transceiver compact. The measured responsivity of the III-V PD in the O-band is about 0.5 A/W (4 orders of magnitude higher than that at the C-band), and the 3-dB RF bandwidth is about 11.5 GHz. The detailed information of the integrated transceiver, for example, the layer information of the PD, the process flow of the transfer printing, the S_{21} responses of the microring modulator and PD, etc., can be found in our previous publication [8].

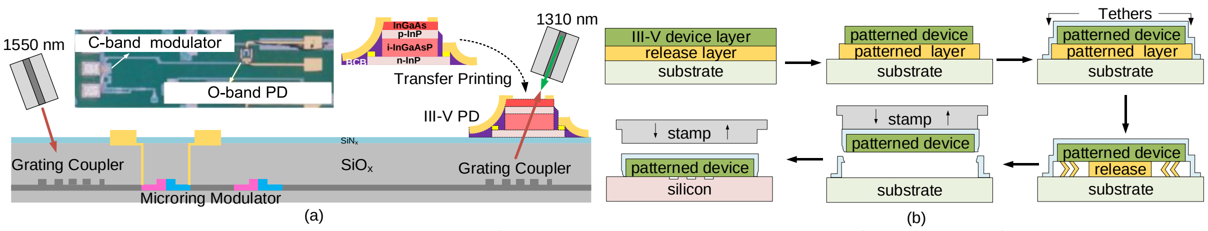

Figure 1. (a) Microscopic image and cross section of the integrated transceiver, (b) schematic flow of the transfer printing process.

Based on the proposed transceiver, a full-duplex analog RoF system can be built, as shown in Fig. 2. In the CO, a C-band optical carrier is coupled into the transceiver from a grating coupler. The optical carrier is intensity-modulated by a downstream signal in the silicon microring modulator, and coupled out of the chip by another grating coupler. The modulated signal is then transmitted to an RRH through optical fiber. In the RRH, the optical signal is demultiplexed by a wavelength division multiplexer (WDM) and sent to a PD, after being amplified by an erbium doped optical amplifier (EDFA). For the upstream link, an O-band laser source is employed in the RRH and sent to an O-band Mach-Zehnder modulator (MZM), which is driven by an upstream signal. The modulated optical signal is duplexed with the downstream signal by the WDM and transmitted back to the CO through the same optical fiber. When the light is applied to the transfer-printed III-V PD, the upstream signal is then converted to the electrical domain.

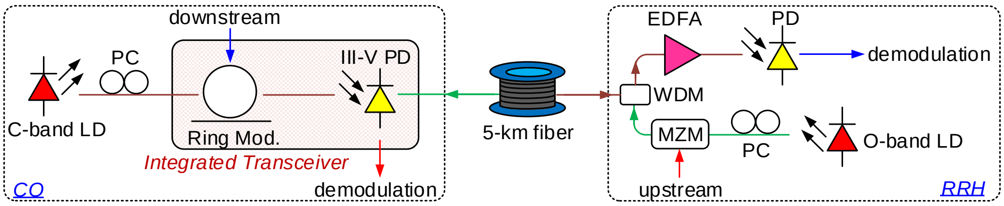

Figure 2. Schematic diagram of the full-duplex analog RoF system based on the integrated transceiver.

3. EXPERIMENT AND RESULTS

An experiment based on the scheme shown in Fig. 2 is carried out. For the downstream link, 12-dBm continuous wave (CW) light generated by a tunable laser source (Santec TSL-510) is coupled into the chip via a polarization controller (PC) in the CO. To ensure efficient E-O modulation, the wavelength of the optical carrier is set to be 1552.128 nm, aligned to the resonance of the microring modulator. Produced by an arbitrary waveform generator (Keysight M9052A), 16QAM data at a 10 GHz carrier frequency with a data rate of 1 Gb/s (250-Mbaud) is amplified by a 10-GHz RF amplifier and applied to the silicon microring modulator, coupled with a 0.7 V DC voltage through a bias tee. The modulated downstream signal is then coupled out and transmitted to a RRH through 5-km single-mode fiber. In the RRH, the downstream signal is amplified by an EDFA and sent to a commercially-available PD with a bandwidth of 20 GHz and a responsivity of ~0.7 A/W. The detected electrical signal is sent to one channel of a 63-GHz real time oscilloscope (Keysight DSA-Z 634A) to realize QAM signal demodulation.

For the upstream link, 5-dBm CW light with a wavelength of 1356 nm is generated by another tunable laser source (Santec TSL-510) and sent to an O-band modulator via another PC. The upstream signal, 250-MBaud 16QAM data with a carrier frequency of 8 GHz, is also generated by the AWG. The modulated O-band upstream optical signal is duplexed with the C-band downstream signal by the WDM and transmitted back to the CO through the same 5-km optical fiber. In the CO, the upstream signal is detected by the transfer-printed III-V PD, which is biased at -1 V, with a responsivity of 0.5 A/W. The output signal of the III-V PD is sent to another channel of the real time oscilloscope for the signal demodulation and analysis.

Fig. 3(a) shows the measured error vector magnitude (EVM) versus the received optical power for the downstream link. As can be seen, for a received optical power of -12.5 dBm, the measured EVM is about 5 %. A clear constellation diagram is observed and shown as the inset in Fig. 3(a). We can also see that, when the 5 km optical fiber is inserted in the link, the EVM is nearly unchanged, which is due to the low fiber transmission loss in the C-band and also the low influence of fiber dispersion for the X-band RF signal transmission. Fig. 3(b) shows the EVM as a function of the received optical power for the upstream link. For a 5-km transmission link, the EVM is <6%, when the received optical power is –6 dBm. It can be seen from Fig. 3(b) that, as compared with the back-to-back (B2B) transmission, the 5-km fiber transmission link introduces a slight deterioration in the EVM, which may result from the relatively higher fiber transmission loss in the O-band. In addition, to check the crosstalk between the C-band downstream and O-band upstream in the O-band PD, a comparison between the EVM results with and without downstream signal transmission is also made. No obvious change is observed from the curves shown in Fig. 3(b).

It should be noted that, since the bandwidths of the microring modulator and the transfer-printed PD are lower than 15 and 11.5 GHz, respectively, the proposed RoF link is designed to work in the X-band. If the microring modulator would be realized in imec’s newest iSIPP50G platform and a modified design is employed for the PD, the bandwidth of the transceiver can be increased, enabling millimetre wave RoF systems.

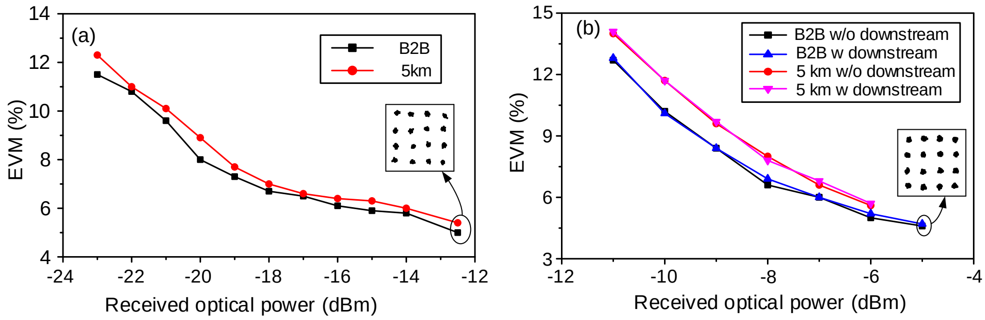

Figure 3. Measured EVM versus received optical power for (a) back-to-back and 5-km downstream link, and (b) back-to-back and 5-km upstream link with the downstream link operational or off. Inset: Constellation diagrams of the demodulated 16QAM signal.

4. CONCLUSIONS

In this paper, we present an X-band full-duplex analog RoF system based on an integrated III-V-on-silicon transceiver. The downstream link transmitter is based on a C-band silicon microring modulator with a bandwidth of 15 GHz, and the upstream link receiver is realized by the integration of an O-band III-V PD with a bandwidth of 11.5 GHz using transfer printing. Error free transmission for both the downstream and upstream links is achieved. We believe that silicon photonics together with transfer printing is an enabling technology to realize low-cost optical devices with high throughput, offering improved performance, cost-efficiency and increased functionality in future wireless communication systems.

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