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Simultaneous microwave characterization of wafer-level optoelectronic transceiver chips based on photonic sampling and mapping

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Photonic integrated circuits (PICs) promise future parallelism growths of high-performance communication, computation, and offer unprecedented bandwidth scalability with reduced power consumption as a viable replacement for an electrical wire with an optoelectronic transceiver consisting of a transmitter and a receiver integrated on the same wafer. This wafer-level photonic integration, however, raises challenges for processing optical-electrical (O-E) and electrical-optical (E-O) characterization, which is crucial in chip fabrication and optimization [1].

Electro-optic frequency sweep method (EOFS) is widely used with the help of a microwave network analyzer (MNA) to convert optical into electrical measurement [1, 2]. In the wafer-level case, the optoelectronic transceiver chip is considered as a cascaded electrical-optical-electrical (E-O-E) link comprising the intensity modulator (IM) chip and the photodiode (PD) chip, and characterized through scattering parameter measurement at the reference planes M1-D2, as shown in Figure 1(a). The detailed transmission and scattering matrices are shown in Appendix A. Since the measured results are contributed by both the IM and the PD, intense calibration must be performed to de-couple the individual response of the IM or the PD by breaking down the integrated transceiver into discrete IM or PD chips to be off-chip coupled with O-E or E-O transducer standards.

To simplify the calibration procedure, we have presented an on-wafer probing kit to realize the damage-free and self-calibrated frequency response measurement of an integrated silicon photonic transceiver based on heterodyne-mixing [3]. It is noted that the on-wafer transceiver chips are assumed with a good impedance match. As we know, the impedance mismatch will provoke multiple reflections or even resonances between the adapter networks and the chip under test, which may greatly affect measurement accuracy [1, 2]. We further proposed the photonic sampling method and demonstrated the measurement of IM [4] or PD chips [5], respectively, regardless of what the impedance is. Nevertheless, the IM chip measurement is assisted by a packaged PD with a good impedance match, and vice versa. Therefore, methods that are capable of simultaneous characterization of a wafer-level E-O-E link even without a good impedance match, and at the same time free of extra E-O or O-E calibration are of great interest.

In this study, we demonstrated for the first time, to the best of our knowledge, that the photonic sampling and mapping technique can be qualified for simultaneously extracting the intrinsic frequency responses of IM chip and PD chip in a wafer-level E-O-E link. More details of the operation principle are provided in Appendix B. As shown in Figures 1(a) and (b), an optical pulse train from a mode-locked laser (MLL) is coupled into the IM chip of the integrated E-O-E link under test via a taper single-mode fiber (SMF1) to sample a microwave signal from the MNA source. Then, the sampling optical pulse train is coupled into the PD chip of the E-O-E link for photodetection with another taper single-mode fiber (SMF2) and the generated photocurrent is collected by the MNA receiver. Both the Mach-Zehnder modulator (MZM) chip and PD chip are electrically contacted by microwave probes (Probe 1, Probe 2, GGB 40A), respectively. In the PD measurement, a fixed-low-frequency modulation signal is up-conversion mapped to every comb line to retrieve the combined response of the PD chip and the receiver adapter network, which is immune to the IM chip. Then, the intrinsic parameters of IM and PD chips are respectively extracted after de-embedding the adapter network A and B, as shown in Figure 1(a), through the short-open-load-thru (SOLT) calibration and power leveling operation [4, 5]. More details of microwave de-embedding are included in Appendix C.

In the demonstration, we specially choose a PIC consisting of a Si-based MZM chip and a Si-based Ge PIN PD chip as the optoelectronic transceiver as the device under test, as shown in Figure 1(a), to make a comparative characterization between the wafer-level measurement with the proposed

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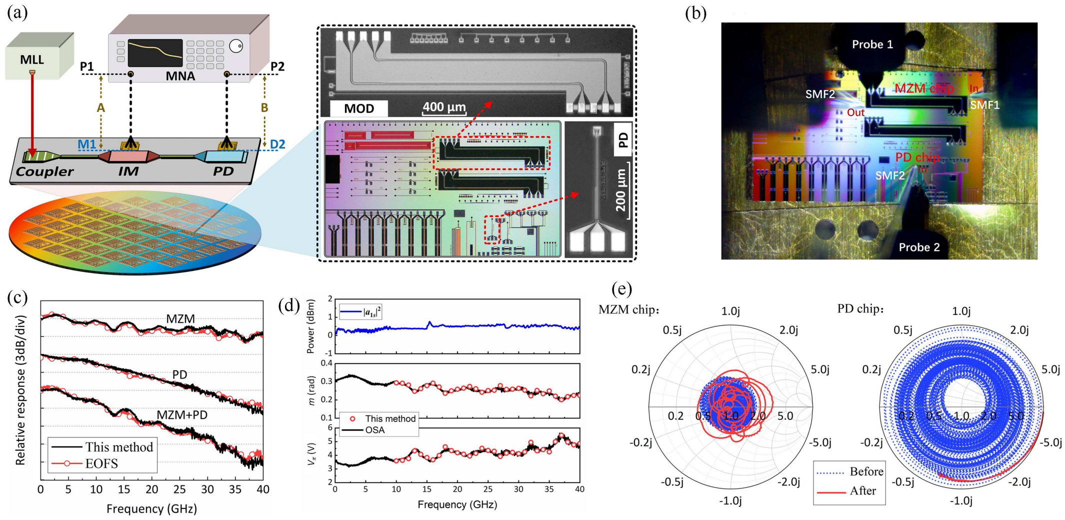

Figure 1 (Color online) (a) Schematic setup of the proposed on-chip measurement method and the photographs of the chip under test. A and B: microwave adapter networks. (b) Measurement set-up for the MZM chip and PD chip. (c) Measured relative frequency responses of the MZM, PD and MZM+PD by EOFS method and the proposed method. (d) Measured modulation depth and half-wave voltage of the MZM chip by the OSA method and the proposed method. (e) Measured reflection coefficients of the MZM chip and PD chip before and after de-embedding the microwave adapter networks on the Smith chart.

method and discrete measurement with conventional EOFS method [1, 2] or optical spectrum analysis (OSA) method. The combined frequency response of the transceiver chip, the modulation index, and the half-wave voltage of the MZM chip can be also obtained by the EOFS method and the OSA method, respectively, as the red circle line shown in Figures 1(c) and (d), which verifies the feasibility of the proposed method. More details of comparison are included in Appendix D. Furthermore, the reflection coefficients of IM and PD chips before and after de-embedding the microwave adapter networks are marked in the Smith chart, as shown in Figure 1(e). More details of reflection coefficients are included in Appendix E. It is found in Figure 1(e) that the MZM chip does not reach a perfect 50 Ω match in the whole modulation frequency range, and the PD chip is with high impedance far from a 50 Ω match. The reflection coefficients of the MZM and PD chip confirm that the proposed method is robust to the impedance mismatch.

In summary, we have proposed intrinsic frequency response measurement for a wafer-level optoelectronic transceiver chip consisting of an IM chip and a PD chip based on photonic sampling and mapping. It enables self-reference measurement of modulation depth, and/or half-wave voltage of high-speed optoelectronic chips. Moreover, it is robust to the impedance mismatch. We believe it is promising for non-invasive characterization of integrated transceiver chips during fabrication, and promisingly offers predictable outcome and yield analysis before packaging.

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Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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