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AWG-Based Photonic Transmitter With DBR Mirrors and Mach–Zehnder Modulators

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***Abstract*— In this letter, we demonstrate a novel monolithically integrated photonic multiwavelength transmitter that was realized by integrating an arrayed waveguide grating-based laser with selective distributed Bragg reflector mirrors and Mach–Zehnder modulators. The integrated circuit was designed according to a generic integration model, by utilizing standardized photonic building blocks, and was fabricated on an InP-based platform in a multiproject wafer run. The device delivers above 1 mW of optical power into the fiber with a side mode suppression ratio better than 40 dB. The linewidth of the generated signals is 275 kHz. We achieved error free 50-km transmission at the modulation data rate of 10 Gb/s per channel, for a received power of −26.5 dBm.**

***Index Terms*— AWG, DBR, generic integration, InP, Mach-Zehnder modulator, multiproject wafer run, multiwavelength transmitter, optical access network, photonic integrated circuit.**

I. Introduction

GENERIC integration technology has brought a paradigm shift in the field of integrated photonics [1], [2] and changed the way photonic chips are developed, designed, fabricated, packaged and also tested. The fundamental change is based on a design method which freely combines just a few standardized and parameterized photonic building blocks [3] to form complex photonic circuits using sophisticated design tools, powerful component libraries and the highest-level manufacturing technologies. These approaches together with the fabrication method organized in multi-project wafer (MPW) runs reflect the need for cost-effective solutions that bring photonic devices within the reach of every entity and for multiple applications.

Already a number of such devices were realized on an indium phosphide (InP)-based platform and recently demonstrated [4]–[6]. In this letter we present a novel InP-based, monolithically integrated 8-channel multiwavelength transmitter (MWT) that was fabricated according to this generic model by an industrial foundry partner [7]. The uniformity, reliability of the platform and high yield are provided by the manufacturing partner, which enabled their technology platform used for fabrication of commercial devices such as tunable laser-Mach-Zehnder PICs employed in tunable XFP-format transceivers. The multiwavelength source implemented within the photonic circuit is based on the operational principle of a linear arrayed waveguide grating-based laser (AWGL) [8]–[10]. These sources use an AWG as intra-cavity filter to determine the generated wavelengths. The lasing wavelength depends on the passband location of each channel of the AWG. The cavity loss is minimal for the specific wavelength corresponding to the particular passband of the AWG, for which the SOA is activated. In the linear configuration of the AWG laser a separate SOA is included for each wavelength, and by biasing more than one SOA at the same time, the source can simultaneously generate several wavelengths. To avoid lasing of the source in the next AWG orders, and thus grating orders different from the central free spectral range (FSR) [11], we implemented into the source wavelength-selective mirrors: DBR gratings. The laser cavity is then formed between the DBR and a cleaved facet (highly reflective: HR coated), as indicated in Fig. 1. This configuration of the multi-channel source allows to freely position the on-chip mirrors, and thus provides flexibility in the resonant cavity length and thus in the longitudinal mode spacing. Recently reported on-chip mirrors, multi-mode interference reflectors [12], provide such flexibility, but are broadband and therefore cannot be used as wavelength selective filters. Lasing in unwanted AWG orders can be avoided with a chirped AWG, but this will complicate the design and increase the intra-cavity loss. By using the wavelength-selective DBR gratings, we suppress lasing in adjacent orders of the AWG. Furthermore, when implementing tunable DBR-based gratings,

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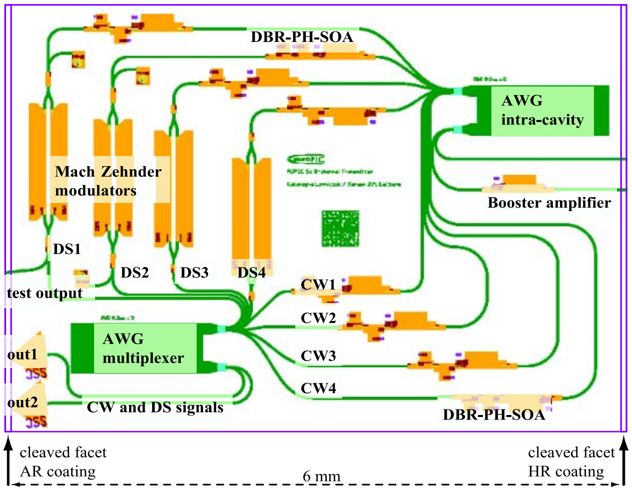

Fig. 1. Mask layout of 4.3 mm × 6 mm photonic integrated transmitters.

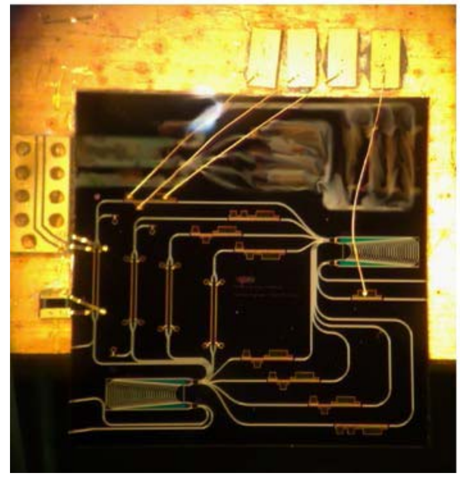

Fig. 2. Mounted and wire-bonded chip on a high RF ceramic submount.

we are able to accurately select the wavelength within the passband of the AWGs, as well as select the operational AWG passband itself. We also obtain a single mode operation without mode hops, and narrow linewidth thanks to the relatively long extended cavity of AWGL. These sources are also easier to drive, as compared to traditional AWGLs, while the tuning precision can be enhanced by introducing phase elements (PH) within the resonant cavity. The proposed configuration of MWT is an alternative design to the MWTs presented in [5] and [13]. The devices reported in [5] and [13] use an array of lasers with an AWG used as multiplexer of optical signals, and external to the cavity.

II. Device Design

The MWT chip integrates the following photonic building blocks (BBs): (1) passive waveguide devices; (2) semiconductor optical amplifiers (SOAs), (3) phase modulators and (4) distributed Bragg reflector (DBR) gratings, (5) detectors and (6) spot-size converters; which gives in total 46 BBs. The device was designed to operate as a key source localized in the central office (CO) part of the optical access network and simultaneously produce both continuous wave (CW) pilot tones that will act as a carrier for the upstream (UP) data and modulated downstream (DS) data, while the modulation data rate should reach 10 GbE per transmission channel.

The mask layout of the fabricated photonic transmitter is presented in Fig. 1. The device measures 4.3 mm × 6.0 mm and integrates an AWGL with four electro-optical Mach-Zehnder modulators (MZMs) and a separate AWG used as a multiplexer. The device was designed to simultaneously operate on 8-channels, where four of the generated wavelengths remain CW signals and four of the generated wavelengths are directed to the MZMs and later used to produce DS data. For our specific application we designed the multiwavelength source with a guard channel, which may be observed in the spectra as an absence of the wavelength peak between generated CW and DS channels. We designed the AWG-based source with the length of the DBR grating section of 150 μm giving 40% of reflection for a grating strength coefficient $\kappa = 50$ cm^{-1}. The DBR grating can be tuned to a shorter wavelength range by current injection. The mode-hop free operation is achieved by aligning two filters: AWG with the 3-dB passband of 0.5 nm and DBR grating with the 3-dB passband of 3 nm. We also introduced a 200-μm-long phase section (PH) within the laser cavity to fine tune the phase of the generated signals. The longitudinal mode spacing is around 0.05 nm. The active sections providing the gain within the structure, namely the SOAs and a booster amplifier, are 500 μm long. The MZM intensity lumped modulators are placed outside the laser cavity. The length of the phase modulators used for the MZM implementation is 1000 μm, which enables more than 10 GHz operation through the quantum confined Stark effect (QCSE). All generated and modulated signals are multiplexed into common optical outputs by a second AWG. The AWGs (the intra-cavity filter and the multiplexer) have identical designs, with a center wavelength $\lambda_c = 1550$ nm, a channel spacing of 100 GHz (0.8 nm), and with a FSR of 900 GHz (7.2 nm). The facet of the chip where the optical outputs are positioned, is anti-reflective (AR) coated.

III. Measurements

The device was mounted on a high frequency submount. One arm of the Mach-Zehnder modulator was wire bonded on one side to a 50 Ω RF transmission line and on the other side to a 50 Ω termination for impedance matching. The DC current injection contact pads of the booster, SOA, PH and DBR grating were wire bonded to external DC pads to ease access during characterization. A tilted lensed fiber was used to couple the light out from the chip. The measurements were performed at room temperature, without active cooling of the device. To determine single mode (SM) operation of the AWGL and measure the side-mode suppression ratio (SMSR) we used a high resolution (0.16 pm) Optical Spectrum Analyzer, APEX P2041A. A photograph of the mounted chip is shown in Fig. 2.

During the first experimental stage and tests of the 8-channel transmitter we were able to wire bond only one out of eight channels, thus most of the presented transmission measurement results will refer to channel DS1, using a test

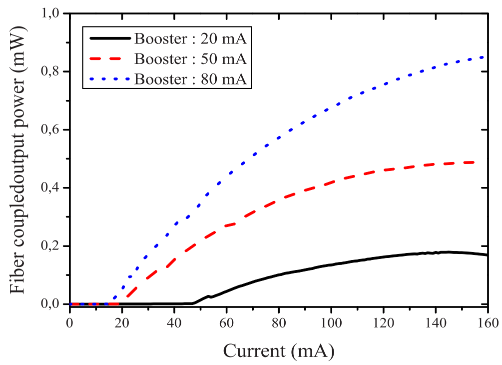

Fig. 3. *LI* characteristics measured for DS1 channel of AWGL while changing the current injected into the booster amplifier.

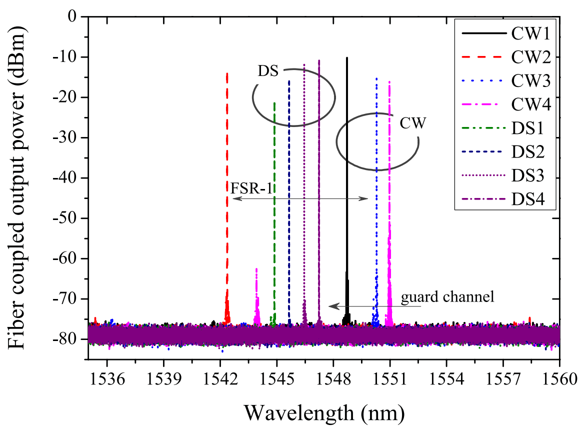

Fig. 4. Spectral characteristics of the MWT while activating each channel consecutively and biasing the booster between 50 mA and 100 mA.

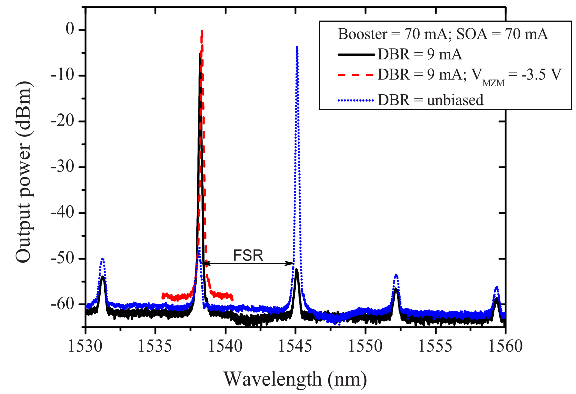

Fig. 5. Detected spectra of DS1 channel while changing bias conditions of DBR grating and Mach-Zehnder modulator.

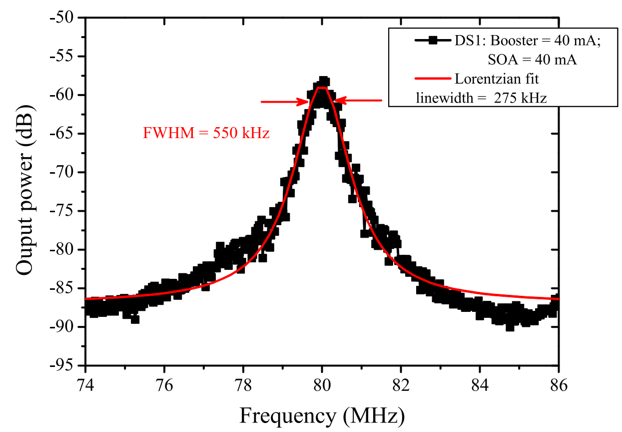

Fig. 6. Measured linewidth of AWG-DBR-laser is 275 kHz.

output, as indicated both in Fig. 1 and in Fig. 2. Nevertheless we expect the performance of all the remained channels to be the same in terms of the modulation data rate.

A. LI and Spectral Characteristics of AWGL

The measured *LI* characteristics of AWGL as well as the threshold currents depend on the current injected to the booster amplifier that was placed in the common waveguide within the laser cavity. After activating the booster with 20 mA and later 50 mA the detected threshold current decreases from 46 mA to 20 mA. The measured characteristics of one of the AWGL channels, channel DS1, are presented in Fig. 3. The early thermal roll-off, and thus the power saturation, indicates a relatively high series resistance present at the SOA BB, which induces additional heating of the gain material. The spectra of the MWT detected for every channel biased one by one is presented in Fig. 4. The measurements were performed while biasing the booster between 50 mA and 100 mA, and activating SOAs between 90 mA and 160 mA. The generated signals were then multiplexed by AWG to the common output. We obtained SM operation for every channel with a SMSR better than 40 dB. The output power varies per channel, since the SOAs and the booster were not optimized for the power equalization. This will be addressed in our further work, while simultaneously operating all the channels of the transmitter, which will require packaging of the device with multiple DC and RF access. The guard channel is visible between the generated DS and CW signals as an absence of the wavelength peak. The passive waveguide loss and bend loss are around 4.5 dB/cm. The AWG insertion loss is 5 dB. The cavity loss is different for a different channel of the laser (different length of passives) and varies between 6.5 dB and 8.5 dB.

The implementation of the on-chip selective DBR mirrors results in stable SM operation of the laser in the FSR determined by the gratings bandwidth. The experiment with tuning of the grating section through current injection is presented in Fig. 5. The measured FSR of the AWG is 7.1 nm. The phase section allows to fine-tune our source within the AWG passband in the range of 0.04 nm. The linewidth of the AWG-DBR source is measured with a self-heterodyne setup to be 275 kHz. We biased both the booster amplifier and the SOA with 60 mA. The linewidth was found as the full width at half maximum after fitting the RF spectrum with a Lorentzian profile. The measurement result is presented is Fig. 6.

B. Static and Dynamic Performance of MWT

The measurements of a static extinction ratio (ER) and for obtaining the bit-error-rate (BER) characteristics were performed on channel DS1 of the MWT. The measured V_π of a 1-mm-long MZM equals 1.4 V (reverse bias) with a static ER better than 25 dB. The test results are presented in Fig. 7. It can be seen that the MZ arms (while not biased) introduce

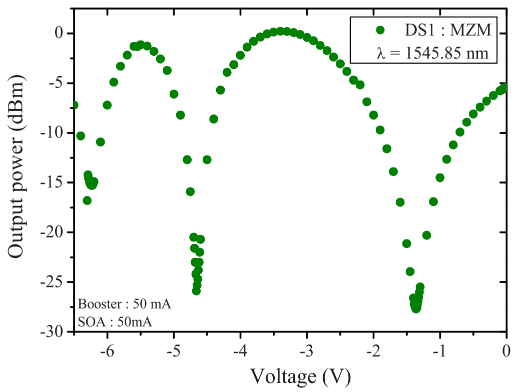

Fig. 7. Static extinction ratio of MZM. The obtained $V\pi$ is 1.4 V (reverse biased) with the static ER better than 25 dB.

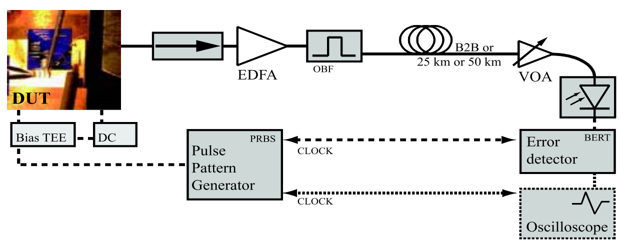

Fig. 8. Schematic of the BER and eye-diagram measurement setups.

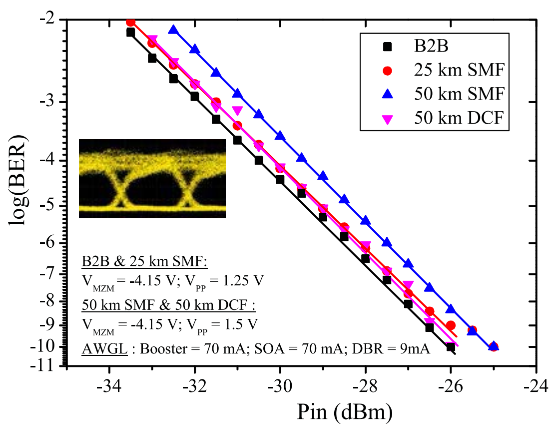

Fig. 9. 10 Gbps BER characteristics detected in B2B configuration and after transmission of the signals in 25 km, 50 km SMF, and 50 km SMF with DCF.

slightly different phase shift, since we did not obtained the maximum transmission at 0 V at one of the MMI outputs. The transmission measurements (both BER and eye-diagrams) were performed using setup presented in Fig. 8. The BER characteristics detected in back-to-back (B2B) configuration and after transmitting signals at distances of 25 km and 50 km are demonstrated in Fig. 9. We used a PRBS signal of the length of 2^7-1 and 2^{31}-1, and no difference of the performance of the device was observed. We applied bias voltage of V_{MZM} = –4.15 V, with optimized for transmission V_{PP} of 1.25 V and 1.5 V. The BER measurements were performed at 10 Gbps and reveal error-free operation of the MWT for the received power of –26.5 dBm with a penalty of only 0.25 dB after introducing 50 km long SMF with dispersion compensating fiber (DCF).

IV. Conclusion

We demonstrated operation of a novel monolithically integrated 8-channel photonic multiwavelength transmitter that utilizes an AWG-based laser with wavelength-selective DBR mirrors and electro-optical Mach-Zehnder modulators. The characterization shows very good performance of the photonic circuit, offering error-free transmission at 10 Gbps per channel at a distance of 50 km (at P_{in} of –26.5 dBm) with an optical output power up to 1 mW in fiber, and narrow optical linewidth of 275 kHz. The device produces both CW signals and DS data, which makes it attractive for utilization in optical access networks. The reported transmitter demonstrates the capabilities of a generic integration processes for developing high-performance devices in low-cost MPW-runs.

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