Integration of MZI modulators and AWG-based multiwavelength lasers in InP

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This paper discusses the integration of arrayed-waveguide grating based multiwavelength lasers and high-speed Mach-Zehnder interferometer modulators in InP. We developed a technology that enables the integration of laterally-contacted SOAs with traveling-wave phase shifters on a semi-insulating substrate. Using this technology we are working on the realisation of a four-channel multiwavelength laser integrated with one and four high-speed modulators, respectively. The latter device of 4×8 mm^2 uses a novel design to multiplex all signals without waveguide crossing into one output guide. In this paper, we will present the design of the multiwavelength lasers and experimental results of the integrated RF-modulator, which shows a bandwidth of 34 GHz.

Introduction and design

Photonic integration is the key for reduction of component volume and cost. In recent years, many integrated devices have been demonstrated. A component very suitable for integration is the laser, since its output can be used as an optical carrier for on-chip processes such as light conversion or modulation. Examples of advanced photonic integrated circuits are a distributed feed-back laser (DFB) with an electro-absorption modulator (EAM) [1], a distributed Bragg reflector (DBR) laser with an EAM [2], and an arrayed-waveguide grating (AWG) based laser (AWGL) with a wavelength converter [3].

The Mach-Zehnder (MZI) modulator is another good candidate for integration with a laser. Combinations with a DFB laser [4] and a DBR laser [5] have been realized. Our goal was to demonstrate the first MZI modulator integrated with an AWGL. An AWGL has the advantage over a DBR or DFB laser that it can not only be utilized as a widely-tunable laser, but also as a multiwavelength laser that generates multiple wavelengths simultaneously. This offers the possibility to integrate multiple modulators with only one AWGL to create an emitter of more wavelengths that can be modulated independently. This is also possible with a multiwavelength array of DFB or DBR lasers, but then always an inherently lossy power combiner is needed or, for a large number of wavelengths, an AWG, which requires precise wavelength alignment.

This paper describes the development and realization of two photonic integrated circuits (PICs). The first PIC is a 4-channel AWGL with one common MZI modulator for all four wavelengths. It consists of an AWG acting as an intra-cavity filter that combines the output of an array of semiconductor optical amplifiers (SOAs). Half of the power in the common output is tapped by a 3-dB 1×2 multimode interference (MMI) coupler and is routed to a MZI modulator, the design of which was described in [6].

The second PIC is a 4-channel AWGL with four MZI modulators and four SOAs, one for each wavelength. Its novel circuit scheme is shown in Fig. 1. A conventional approach

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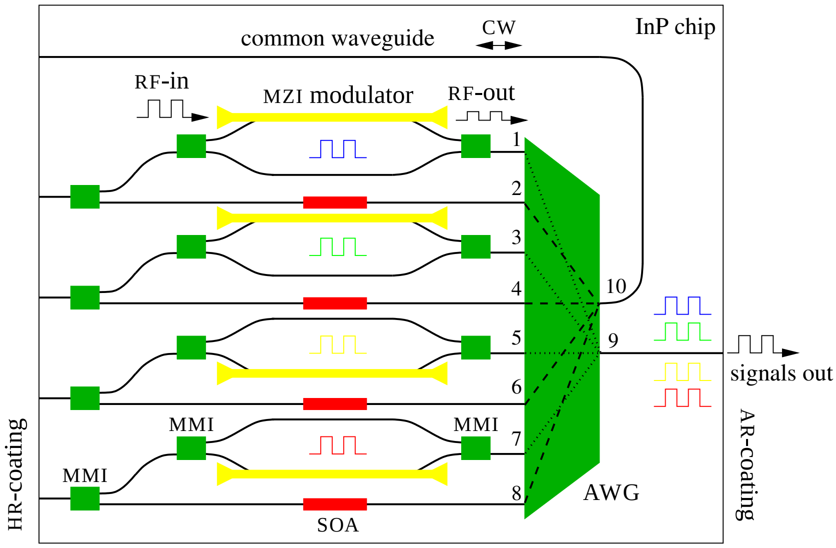

Figure 1: *Schematic of the 4-λ multiwavelength laser integrated with four modulators.*

would need three (de)multiplexers: one in the multiwavelength laser and two at both ends of the four modulators, for demultiplexing and multiplexing the four wavelengths before and after modulation, respectively. This introduces complications: a large chip space is needed and all (de)multiplexers should be accurately tuned to each other. A much more compact circuit design would be possible with the modulator integrated in the laser cavity. This is not possible, however, because a modulator inside the cavity would make the laser to be switched on/off, which process would be too slow for multi-GHz operation because of the large cavity length (~ 1 cm). The new approach of Fig. 1 performs all required multiplexing and demultiplexing operations with a single AWG. By using just one AWG, the device size is small and possible AWG misalignment problems are avoided. The AWG has two inputs and eight outputs. It was designed with a central wavelength of 1556 nm, a channel spacing of 1.6 nm and a FSR of 19.2 nm.

To explain the operating principle of this device, we labelled all AWG ports in Fig. 1. At the right side of the AWG, the port with label 9 is the common output for fiber coupling and the port with label 10 is the common output that leads to a HR coated facet. This waveguide is part of the laser cavity. At left side of the AWG the demultiplexed ports are labelled 1 to 8. The even port-numbers (2, 4, 6 and 8) are each part of a different laser cavity (one for each wavelength) and are connected to 2-µm-wide, 1000-µm-long SOAs. From there, the cavities are completed by waveguides that lead to the HR coated facet.

In each cavity, a 1×2 MMI is included to couple out half of the light reflected from the facet. This light is routed to a separate MZI modulator. They each modulate the microwave signals onto the optical carrier coming from the laser cavities. The four modulated signals at the uneven port-numbers (1, 3, 5 and 7) are multiplexed by the AWG to output port 9.

Both PICs have been fabricated in two successive fabrication runs, in which a number of technological problems have been identified and solved. In the next subsection, we discuss the fabrication technology that was used for the integration of the laser the and modulator structures on a single chip and we explain the the experimental results.

Technology and characterization

The integration of passive waveguides, optical amplifiers and RF phase shifters for use in a laser-modulator device requires optimization of the following issues: optical propa-

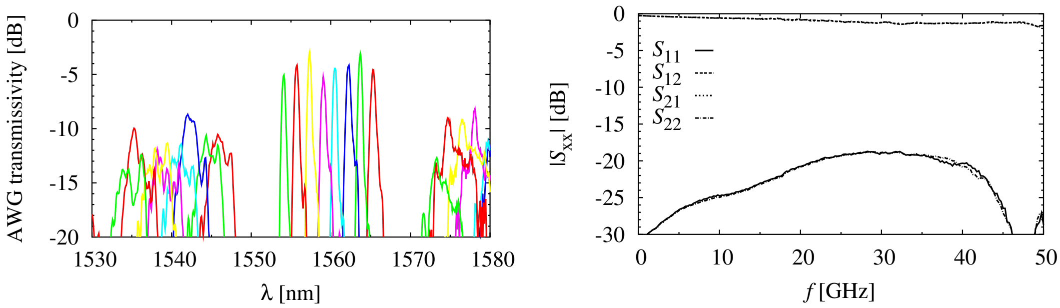

Figure 2: *Measured chirped* AWG *passbands (*left*) and measured small-signal S-parameters of a* CPW *feed line with a length of 1.4 mm (*right*).*

gation, optical reflections, microwave coplanar waveguide (CPW) feed-line propagation, microwave phase-shifter propagation and SOA contacts. For the amplifiers, we developed a lateral n-metalization since the semi-insulating substrate does not allow for back-side metalization. For the waveguide etch, we applied both a Ti-mask and a SiN_x-mask to obtain different etch depths. This resulted in a 1-µm-wide deep waveguide with an attenuation of 11 dB/cm and a 2-µm-wide shallow waveguide with an attenuation of 1.5 dB/cm. In order to investigate the optical propagation through passive waveguides, we cleaved off, and separately measured, the AWG of the device with four modulators. This AWG was chirped [7] to ensure lasing in a predefined AWG order. Figure 2 (*left*) shows the measured AWG transmission curves.

Any microwave attenuation in the CPW feed lines will decrease the measured bandwidth of the modulator. This is because the higher frequencies will be more attenuated by the CPW feed line than the lower frequencies. Any attenuation in the CPWs from the phase shifters to the loads does not affect the modulation bandwidth as the microwave signal has already been modulated onto the optical carrier. We succeeded in fabricating low-loss CPWs using electro plating of gold. Fig. 2 (*right*) shows the measured *S*-parameters of a 1.4-mm-long long CPW with a signal width of 6.8 µm, a gap of 5.6 µm and a ground line width of 50 µm. From the low reflection ($S_{11}, S_{22} < -18$ dB), it can be concluded that the impedance of the lines is close the 50 Ω impedance of the network analyzer. The extracted impedance value at 40 GHz is $53 \pm 2\,\Omega$. The transmission values (S_{12}, S_{21}) have dropped by only 1 dB at 40 GHz compared to the low frequency value.

The microwave propagation in a phase shifter is characterized by two parameters: velocity and attenuation. The quality of the gold electrode on top of the MZI arm is of great influence on the microwave attenuation. The difference between the poor gold quality we had in the first fabrication run and the good quality of the second fabrication run is reflected in the small-signal *S*-parameter measurements on the modulator. In Fig. 3, a comparison is made between 2-mm-long phase shifters made in the first and second fabrication run, measured at a reverse bias of 5 V.

Several observations can be made. Firstly, for the second run, the S_{12} and S_{21} parameters start at a lower DC attenuation ($\sim$ 1 dB) than for the first run ($\sim$ 4.5 dB). This confirms that the gold quality has improved. Also the lower DC resistance confirmed an improvement of the gold quality. Phase shifters of 2 mm in length now had a resistance of $17.98 \pm 4.15\,\Omega$. This is more than a factor two lower than for the first fabrication run. Secondly, the increase of the attenuation as a function of the frequency is less rapid: in the first run, the S_{12} and S_{21} parameters have dropped by 11 dB at 50 GHz, whereas this drop was only 7 dB at 50 GHz in the second run. From these measurements, we extracted the

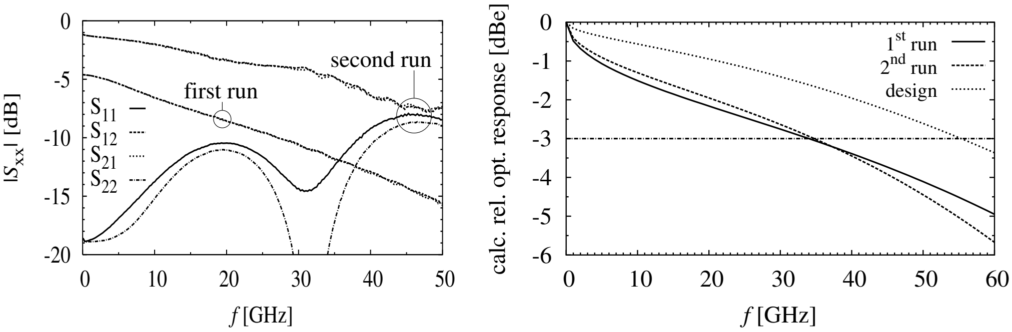

Figure 3: *Measured S-parameters of a modulator with a phase-shifter length of 2 mm (*left*) and calculated bandwidth extracted from S-parameters measurements (*right*).*

modulator impedance ($49 \pm 3\,\Omega$) and calculated the modulator bandwidth (Fig. 3 (*right*)). The expected bandwidth of the designed modulator is more than 55 GHz. The extracted bandwidth of the modulator of the first fabrication run was 34 GHz. The difference was only caused by the higher microwave attenuation in the gold, since the velocity match of this device was almost perfect. The modulator of the second fabrication run had a lower microwave attenuation than that of the first run, but experienced a slight velocity mismatch. This resulted in a similar bandwidth value (34 GHz), which is sufficient for 40 Gb/s operation.

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