

Design of a Photonic Integrated Circuit (PIC) for a BOTDR read-out unit

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Foundry services for PICs open the way to realize economically complex optical functionality. In the expanding field of fibre sensors Brillouin scattering is a powerful effect for determining strain and temperature distributions along fibres. However, the high cost of the optical circuitry has prevented wide use of this technique. Here a design study is reported for a foundry-based Brillouin Optical Time Domain Reflection (BOTDR) read-out unit with low-cost potential. The circuit contains narrow linewidth tuneable DBR-lasers, photodiodes with an optical mixer for coherent detection, a switchable delay line for frequency tuning and a switching fabric which allows three modes of operation.

1 Introduction

With Brillouin scattering it is possible to use the fibre as a sensing medium for monitoring of large constructions. In this way strain and temperature distributions along the length of the fibre can be determined [1]. BOTDR (Brillouin Optical Time Domain Reflectometer) needs however complex and therefore expensive optical circuitry. Foundry services [2] could provide this, since by cost sharing relatively cheap complex optical chips can be obtained. In this paper we report on the design study of a Photonic Integrated Circuit (PIC) capable of providing the optical functionality for BOTDR-systems.

2 Brillouin scattering and BOTDR

If light is injected into a fibre acoustical phonons cause Brillouin scattering, which is downshifted in frequency by around 11 GHz. It can be used to determine the temperature and strain along an optical fibre [3]. With Optical Time Domain Reflection (OTDR) localized information of the fibre condition is obtained. BOTDR analyzers use a narrow linewidth laser to inject a short pulse into the fibre. The backscattered Brillouin light is mixed with light of the source laser for coherent detection. By determining the backscattered signal frequencies around the Brillouin peak and the time delay the status of the fibre at each point along its length can be reconstructed.

3 Circuit design

The BOTDR optical circuit (see Fig 1) is designed around a Mach Zehnder Interferometer (MZI) switch (switch 2). It connects narrow linewidth lasers, a coherent receiver and the sensing fibre. The switch is used to create a pulse entering the fibre. After that, the backscattered Brillouin light and the source laser light are fed into the coherent receiver where their mixed signal is detected. The circuit contains two tuneable

lasers separated by about 11 GHz in frequency. MZI switch 1 selects either of these lasers, allowing both homodyne and heterodyne detection. For homodyne detection light from the downshifted laser enters the coherent receiver. It matches in frequency with the Brillouin signal. A laser locking technique (described below) fixes the lasers at a controllable frequency difference. This allows determining the full Brillouin spectrum. For heterodyne detection only one laser is used to generate the pulse and the local oscillator signal. Fast RF-electronics (around 11 GHz) is required to extract the Brillouin spectrum in that case.

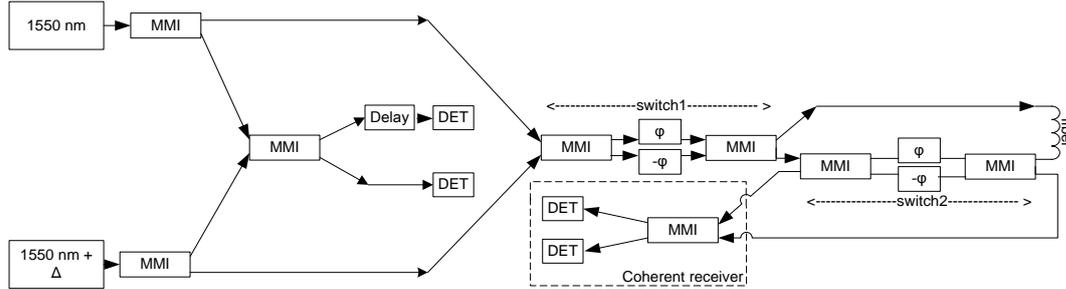


Figure 1: Schematic representation of the BOTDR circuit.

The chip has an extra output available to connect to the other end of the fibre. This allows a third mode of operation: BOTDA (Brillouin Optical Time Domain Analysis). MZI switch 1 is then used to direct light of the two lasers to either end of the fibre. The light entering the back end of the fibre matches the Brillouin frequency, which leads to amplification of the Brillouin backscattering. The full circuit is thus capable of supporting various ways of performing BOTDR measurements. This shows the flexibility that is obtainable by implementing such optical circuit in a photonic integrated chip.

3.1 Lasers

The circuit of fig. 1 contains two tuneable DBR lasers. Each consists of front and rear gratings and a SOA gain section. The rear grating should ensure a high reflection and single mode operation, while the front grating is used for coupling out the light. The laser

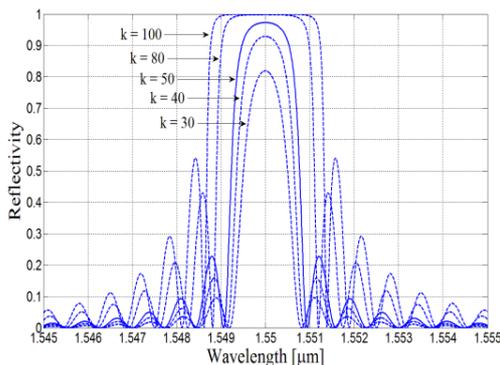


Figure 2: Reflectivity of a 500μm length DBR grating with $\lambda_B = 1.55\mu\text{m}$ versus the wavelength for different values of the coupling coefficient k .

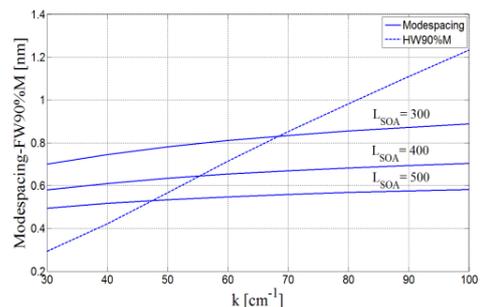


Figure 3: Mode spacing and the half width at 90% of the maximum (HW90%M) as a function of κ for a rear grating of 500 μm length and a front grating of 100 μm. The mode spacing is calculated for different SOAs lengths (μm).

parameters have been optimized according to foundry rules. For high reflectivity the rear

grating has the maximum length (500 μm). Figure 2 shows the calculated reflectivity spectrum for this grating [5] for different values of the coupling coefficient κ . The central wavelength $\lambda_B = 1.55 \mu\text{m}$, with a grating period of 237.51 nm. The value of κ is a trade-off between high reflection and single mode behaviour. Laser simulations show that $<10\%$ suppression of the side modes is enough for single mode operation. Therefore the mode spacing should at least be comparable to the half width at 90% of the maximum reflection of the DBR grating. Figure 3 compares the mode spacing and this half width as a function of κ , with different SOA lengths. The highest reflection while still single mode behaviour can be expected is obtained for $\kappa = 50 \text{ cm}^{-1}$. The 100 μm front grating has a reflectivity of 20%. The SOA has the longest allowed length (500 μm), to have an output power of at least 10 mW. The two lasers differ in frequency by a tuneable value in the range of 10-12 GHz. Tuning is obtained by injecting a small current (nA) in the rear grating.

3.2 Laser locking

The circuit includes two extra detectors and a delay line connected to the two lasers. Combined with a PID controller it provides locking of the frequency spacing between the lasers [6]. Figure 4 illustrates this technique. Light from the lasers is mixed in a 2x2 MMI-coupler. The phase difference between the detector signals is determined with an electrical mixer, and used as an input to the controller, which minimizes the phase difference by tuning the laser frequency. The minimal phase difference occurs if the length of the optical delay equals half the beatlength of the mixed laser signals.

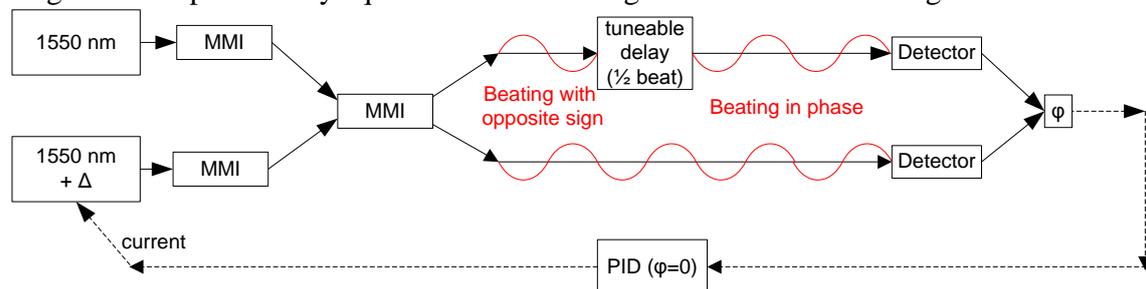


Figure 4 Laser locking with use of a delay line.

The delay should be tuneable for a frequency difference in the range of 10-12 GHz. This is achieved with a 10-bits switched delay line, using a digital coding system [7]. The delay line consists of a chain of delaying elements (see top of fig. 5). In each element light is split over two optical paths. Each patch contains a SOA gate switch, which either blocks or amplifies the light. Thus light is selected from a longer path or a shorter path. The path length over the chain can be tuned over 1024 different values. The smallest delay step is $2 \times 0.38 \mu\text{m}$, corresponding to 2 MHz. With this step the complete desired 2 GHz frequency range is addressed with the delay line. A spiral is added to one of the arms of the delay line to set the centre of the tuning range at 11 GHz. The size of the delay line is 4x2 mm.

4 Chip layout

The layout of the full circuit is shown in figure 5. It measures 6 by 3 mm. Most of the space is taken by the delay line (upper part). Below the delay line the two lasers are

placed, as well as the MZI switches. The BOTDR input and output are at the bottom of the layout. Extra in and outputs as well as detectors are added for testing purposes.

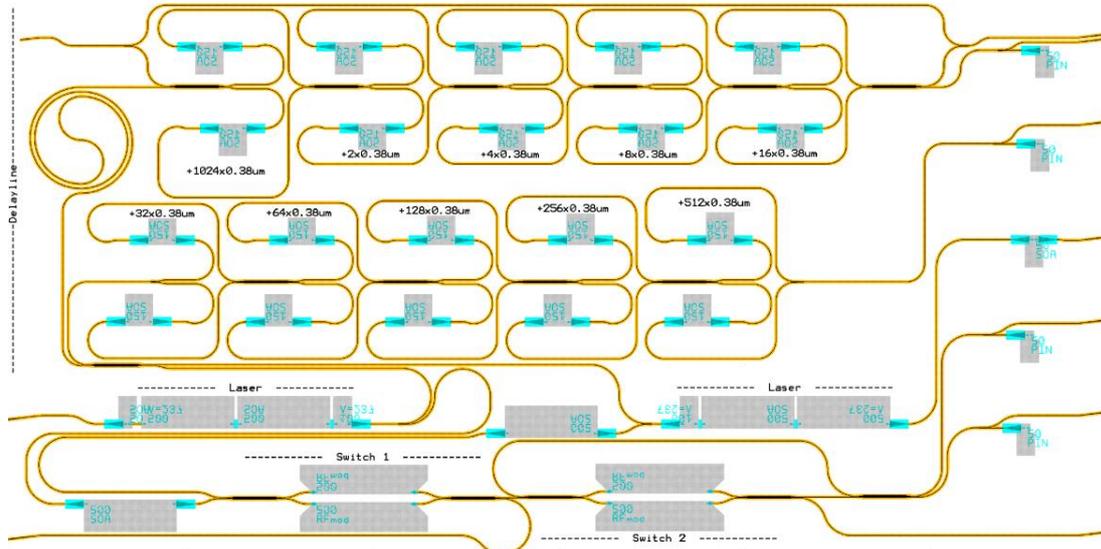


Figure 5: Layout of the integrated BOTDR chip.

5 Conclusions and discussion

A design is presented for an integrated read-out unit of a Brillouin sensor. The optical circuit is designed for realization in a foundry production facility, as is being developed in the European EuroPIC-project. The size is such that several tens of circuits can be obtained from one single 2-inch wafer of InP. This would allow a sizeable cost reduction compared to present commercial BOTDR-systems and BOTDR sensing can become as successful as fibre Bragg grating sensors. As such the integrated BOTDR read-out unit is an example of photonic integration making its way into economically viable applications.

Acknowledgements

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References

- [1] T. Horiguchi and M. Tateda, "Optical-fiber attenuation investigation using stimulated Brillouin scattering between a pulse and a continuous wave," *Opt. Lett.* 14(8), 408-410 (1989)
- [2] M. K. Smit, "Past and future of InP-based photonic integration," *LEOS 2008*, 2008, pp. 1-2.
- [3] T. Kurashima, T. Horiguchi and M. Tateda, "Distributed-temperature sensing using stimulated Brillouin scattering in optical silica fibers," *Opt. Lett.* 15(18), 1038-1040 (1990)
- [4] T. Kurashima, T. Horiguchi, H. Ohnot, and H. Izumita, "Strain and temperature characteristics of Brillouin spectra in optical fibers for distributed sensing techniques", *ECOC98*, Madrid, Spain, p. 149.
- [5] M. Yamada and K. Sakuda, "Analysis of almost-periodic distributed feedback slab waveguides via a fundamental matrix approach", *Appl. Optics*, Vol. 26, N. 16, August 1987
- [6] Yun Li, Xiaoyi Bao, Fabien Ravet, and Evgueni Ponomarev, "Distributed Brillouin sensor system based on offset locking of two distributed feedback lasers", *APPLIED OPTICS / Vol. 47, No. 2 / 10 January 2008 / Page 99 – 102*
- [7] F. Soares, "Photonic integrated true-time delay beamformers in InP Technology", Ph.D.-thesis, Eindhoven University of Technology, 2006