Fiber Bragg grating sensor based on external cavity laser

Citation for published version (APA):
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We present a fiber Bragg grating (FBG) sensor that consists of an external cavity laser where the cavity is formed between a photonic integrated circuit and the FBG. Lasing occurs at the Bragg wavelength and is shifted spectrally according to the sensed physical quantity, which is measured with an integrated interrogator. Whereas typical FBG sensors require an external broadband source, the solution presented here overcomes this by building an integrated laser source using the FBG as a cavity mirror. We demonstrate its functionality by sensing the FBG temperature.

Introduction

The generic integration of active and passive photonic components in a single chip has proved to be successful in the application of photonic integrated circuits (PICs) for diverse applications [1], such as fiber Bragg grating (FBG) sensing. The FBG is a narrow-band reflector whose central wavelength shifts due to external perturbations (e.g. temperature or strain in the fiber) [2]. Therefore measuring the reflected wavelength provides information about the measurand. The typical photonic integrated solution considers an on-chip interrogator (i.e. wavelength meter) and an external broadband source [3], achieving a wavelength resolution in the range of half picometer [4] to a few picometers [5]. In this approach, a significant optical power and polarization control are required, thereby an integrated broadband source (relying on spontaneous emission) is not a practical implementation.

In this contribution, we propose an alternative solution based on the external cavity laser to achieve both source and interrogator integrated in the chip. In the next section we describe the FBG sensing system at a circuit level. Then, we provide the characterization of the integrated laser. In the fourth section, we present the characterization of the integrated interrogator as well as sensing experiments and, finally, we present the conclusions.

Sensing system

The sensor PIC is depicted in Fig. 1a. The laser cavity is formed between an on-chip reflector (i.e. multi-mode reflector, MIR) and the off-chip FBG, and optical gain is provided by a 1 mm long semiconductor optical amplifier (SOA) section. The laser operates always at the Bragg wavelength $\lambda_B$ whose reflection peak shifts spectrally as the result of perturbations to the FBG, and has an out-coupling channel to the integrated interrogator through a 2x2 multi-mode interferometer (MMI).

The interrogator is a spectrometer consisting of an arrayed waveguide grating (AWG) which is designed to have a high crosstalk between neighboring channels, and an array of photodetectors (PDs). High crosstalk is required in order for the laser signal to reach
at least two PDs and therefore be able to monitor its wavelength shift as discussed below. The high crosstalk is achieved by splitting the laser power with a 1x2 MMI thereby having two AWG inputs (hereafter dual-input AWG) close to each other (625 nm spacing) carrying the same signal. As a result, the effective AWG passband broadens and the crosstalk level is increased.

As seen in Fig. 1a, the photonic system has three optical ports (OP) for characterization purposes. OP2 was used to measure the dual-input AWG response and OP3 for characterizing the laser. OP1 can be used for the single-input AWG characterization, nevertheless its use is not discussed in this contribution.

![Figure 1: (a) Schematic of the photonic chip coupled to an FBG fiber. (b) The fabrication of the chip was carried out in the generic PIC platform of SMART Photonics through a multi-project wafer (MPW) run. The AWG has 16 arms and was designed for a 32 nm free spectral range and 4 nm channel spacing.](image)

**Characterization**

**External cavity laser and interrogator**

The chip was edge coupled by a lensed fiber to an FBG fiber with $\lambda_B = 1546.9$ nm and 3-dB bandwidth of 48 pm. We observed lasing at the Bragg wavelength, and measured the laser power and spectrum through port OP3. Figure 2a shows the current-voltage and light-current characteristics of the laser. Power oscillations are visible above threshold operation, presumably due to instabilities producing mode hopping. The major instability came from the mechanical vibrations of the fiber tip at the chip-to-fiber coupling.

We varied the temperature in the FBG fiber by means of a water cooled system. Figure 2b shows a red shift of the lasing spectrum for higher temperatures. This experiment demonstrated that the integrated source is able to operate at the Bragg wavelength regardless of its shift caused by a physical disturbance.

Once demonstrated that the external cavity laser presents a clear threshold, it provides a significant amount of power for the application and is always locked at $\lambda_B$, we carried...
out the characterization of the integrated interrogator and performed dedicated sensing experiments to demonstrated its functionality.

We characterized the dual-input AWG response by means of an external tunable laser feed into port OP2. Figure 3a shows the AWG transmission measured at two output waveguides through the PDs, nevertheless all eight channels displayed similar characteristics. The crosstalk level is higher than -3dB which is enough to detect the laser power at two different photodetectors (PD1 and PD2). In order to translate the measured photocurrents into a value representing the wavelength shift, an interrogation function is used. We employ the following function \( R = (I_{PD1} - I_{PD2}) / (I_{PD1} + I_{PD2}) \), where \( R \) is the interrogation function value, and \( I_{PD1}, I_{PD2} \) are the photocurrents at PD1 and PD2, respectively. Figure 3a(right axis) shows the interrogation function evaluated with the PD1 and PD2 response (left axis) with a slope of -0.7 nm\(^{-1}\) in the central part. The same function can be evaluated over the rest of the PDs to cover a larger bandwidth, however for many applications a narrow spectrum is enough (e.g. for temperature sensing \( \sim 1\text{nm}/100^\circ\text{C} \) can be expected).

**Sensing experiments**

Finally, we performed two sensing experiments with different laser sources in which we evaluated the interrogation function with one thousand measurements taken continuously during \( \sim 10 \) minutes. In the first experiment, we feed the interrogator with an external laser at 1549 nm through port OPT2, whereas in the second experiment we employed the integrated laser operating at \( \lambda_B \) for which we used a different set of PDs. Figure 3b shows histograms for both cases, with a standard deviation corresponding to 0.75 pm and 2.5 pm for the external tunable laser and integrated external cavity laser, respectively. The first experiment reveals the ultimate resolution achievable with our interrogator given the experimental conditions used taking into account temperature stabilization (\(< 0.01^\circ\text{C}\) and electronic noise from standard NI-9207 data acquisition (200 nA RMS noise). In the second experiment, the resolution is reduced due to additional factors, such as the lasing spectrum having a finite width, polarization conversion noise and mechanical vibrations.

Figure 2: (a) Current-voltage and light-current characteristics. The threshold point corresponds to a current density of 2 kA/cm\(^2\). A maximum power of 1.5 mW was measured. (b) Lasing spectra for different FGB temperature consisting of hundreds of non-resolvable Fabry-Perot lines. A lasing peak shift of 7.7 pm/\(^\circ\text{C}\) was found.
Figure 3: (a) Dual-input response of AWG measured at two PDs with -2V reverse bias. (b) Histogram of interrogation function evaluated when using (left) an external tunable laser and (right) the integrated external cavity laser. A normal distribution is superimposed (dashed line).

at the fiber tip. The latest was observed to be the most severe factor.

Conclusions

We demonstrated a novel approach to integrate the light source and interrogator in a single photonic chip for FBG sensing applications. The system is fully functional and the concept can be extended to multiple fibers (one SOA per fiber) or multiple FBGs in a single fiber (sharing the same SOA), using the same interrogator. As expected, the resolution of the full system (2.5 pm) was lower than that of the pure interrogator (0.75 pm) due to additional noise factors, nevertheless it can be improved by e.g. packaging the chip, using an FBG with narrower bandwidth and introducing polarization control.

Acknowledgments

V. D.-C. would like to acknowledge Bright Photonics for the AWG design module license, and Nicola Calabretta for facilitating the FBG fiber for the experiments.

References