High-Resolution AWG-based fiber bragg grating interrogator

Citation for published version (APA):

DOI:
10.1109/LPT.2016.2587812

Document status and date:
Published: 15/10/2016

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 11. Apr. 2021
High-Resolution AWG-Based Fiber Bragg Grating Interrogator

Dzmitry Pustakhod, Emil Kleijn, Kevin Williams and Xaveer Leijtens

Abstract—A novel InP-based monolithically integrated multi-wavelength detector is used as the central part of a fiber Bragg grating interrogator unit. We have designed the arrayed waveguide grating (AWG) in the device such that at least two detectors have a significant signal at any wavelength being measured. Consequently, the measurement resolution is increased, while keeping the area of device small. We demonstrate the resolution of the measurement to be 0.32 pm over a working range of 10 nm. The corresponding relative resolution of 0.003% is to our knowledge the best reported to date in an integrated interrogator.

Index Terms—Photonic integrated circuits, optical waveguide filters, fiber Bragg grating

I. INTRODUCTION

FIBER Bragg Grating (FBG) sensors are currently used in several important applications such as structural monitoring and chemical sensing [1]. In such sensors, the FBG embedded into a fiber works as a wavelength-specific reflector: only a narrow-band line is reflected back if the grating is illuminated with a broadband source. A change of the fiber properties at the location of the FBG sensor, due to strain or temperature change, will cause a variation of the refractive index or the pitch of the grating. This in turn results in a shift of wavelength of the reflected signal. Typical values of the response to change of the mentioned measurands near 1550 nm are ∼1.2 pm/microstrain and ∼13 pm/°C [2]. To track the change of the wavelength of the reflected light, FBG interrogators (FBGI) are used.

Current commercial FBGIs have a resolution of a few pm, and they are relatively large and expensive units. The typical static resolution of such sensors is in the order of 2–4 microstrain (2.5–5 pm) [1], [3], [4]. Recently several approaches to use photonic integration to reduce the size and cost of the units were made [5]. The achieved resolution expressed as an RMS wavelength measurement noise δλrms ranges from half a picometer [6] to a few picometers [7]. The better wavelength resolution, however, can usually be achieved at the expense of the measurement range of the interrogator, which is another important performance parameter for such devices. In order to compare various devices we will use the relative resolution, i.e. the ratio between the resolution and the full measurement range, as a figure of merit. A record relative resolution demonstrated in literature is 0.02% [8] (a resolution of ±3.5 microstrain over 20 nm wavelength range).

In this letter we present a novel AWG-based FBGI, which ensures a significant signal in at least two outputs. The device features monolithically integrated photodetectors. We present the general description of the interrogator, and the modifications to improve the interrogator performance in Section II. In Section III the simulated performance of the device is shown. Section IV presents the measurement results of the fabricated chip. In Section V we give an analysis and discussion of the interrogator performance based on these measurement results.

II. FIBER BRAgg GRATING INTERROGATOR DESIGN

The schematic of the interrogator unit is depicted in figure 1. Light is coupled from the fiber into the device through the cleaved chip facet with an anti-reflection coating (In1, In2). In normal AWG operation (In2), the light reaches the input of an arrayed waveguide grating (AWG) after propagating through the waveguide. After transmission through the AWG it is directed to an output waveguide depending on the wavelength of the light [9]. Light is then detected by the integrated PIN photodiodes. The photocurrents from the diodes are measured and are used for determining the wavelength of the incoming light.

Manuscript received XXXX XX, 2016. This work was carried out in the ProCon Project 11369, supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO), and which is funded in part by the Dutch Ministry of Economic Affairs. The main results of this paper are presented at the 18th European Conference on Integrated Optics, Warsaw, Poland, May 2016.

The authors are with the COBRA Research Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands (e-mail: d.pustakhod@tue.nl).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/
In our approach, we modify the input waveguide by inserting a $1 \times 2$ MMI coupler (see figure 1 and 2, In1) and connecting both outputs ($\alpha$ and $\beta$ in figure 2) to the star coupler of the AWG. This adds a second peak in the spectral response of each detector, and the position of the peak can be controlled by the distance between waveguides $\alpha$ and $\beta$. In our design this distance corresponds to $2.5 \times \Delta f_{ch}$ in spectral response. In this way we ensure a readout at any wavelength on at least two detectors, and we can make use of a differential technique, described in more detail in Section IV.C.

![Fig. 2. Design of AWG inputs. In1 is the modified input used in the interrogator with a $1 \times 2$ MMI in the middle. $\alpha$, $\beta$—outputs of the MMI. In2 is a standard AWG input.](image1)

### III. SIMULATIONS

We simulated the response of the interrogator using an analytical model [11]. The transmission spectra for channels 4 to 8 of the AWG with the modified input are shown in figure 3a. Each output has two peaks in the passband ($\alpha$ and $\beta$), the separation between them $\Delta \lambda_{\alpha,\beta}$ is determined by the distance between inputs $\alpha$ and $\beta$ in figure 2. In the designed device $\Delta \lambda_{\alpha,\beta} = 2.5 \Delta \lambda_{ch}$. The channel spacing is $\Delta \lambda_{ch} = 3 \text{ nm}$. The simulated central wavelength of the AWG $\lambda_0$ was corrected to match the position of measured passbands.

### IV. MEASUREMENTS

The device design was made following a generic integration methodology, using standard building blocks such as waveguides, AWG, and detectors [12]. The fabrication of the device was done in a Multi-Project Wafer (MPW) run carried out at Oclaro Technology Ltd. The platform used is based on ridge-type waveguides in InP with and active-passive butt joint integration. Figure 4 shows a photograph of the fabricated device.

![Fig. 4. Microphotograph of the fabricated device.](image2)

#### A. Characterization Setup

For the characterization of the transmission properties of the device, we use a tunable laser (Agilent 81940A) with a linewidth $\Delta f = 100 \text{ kHz}$ and wavelength stability of $\pm 2.5 \text{ pm}$ over 24 hours as a light source. The device is designed for TE polarization and the polarization handling is done off chip. TE polarized light is coupled into the chip through the input In1 in figure 1 with a lensed fiber tip. The extinction ratio between TE and TM is $20 \text{ dB}$. The photocurrent from the reversely biased detectors is recorded using NI9207 current meter module with a sampling rate of 20 Hz.

The optical power from the laser is $P_{TLS} = 10 \text{ dBm}$. Taking into account coupling loss of $\alpha_c = 4 \text{ dB}$, the optical power on-chip is $P_{chip} = 6 \text{ dBm}$. Photodetector responsivity is $R_{pd} = 0.8 \text{ A/W}$. This gives a photocurrent of $\sim 0.7 \text{ mA}$ considering a $3 \text{ dB}$ splitting ratio on the MMI coupler and AWG insertion loss of $IL_{AWG} = 3.5 \text{ dB}$.

The positions of the AWG passbands are dependent on the temperature of the chip. For InP-based devices the temperature dependent wavelength shift is around $K = 0.12 \text{ nm/}^\circ\text{C}$ [13], which means that to achieve wavelength measurement resolution of 1 pm the chip temperature should be kept stable within $0.008^\circ\text{C}$. In our setup we have used passive thermal isolation to ensure a stable operation temperature. Such an arrangement provides a more stable readout compared to one with active temperature stabilization.

#### B. AWG Passbands

The measured photocurrent for three channels is shown in figure 3b. The channel spacing of the fabricated device is $\Delta \lambda_{ch} = 3.0 \pm 0.1 \text{ nm}$ and the distance between the peaks is $\Delta \lambda_{\alpha,\beta} = 7.5 \text{ nm}$, which matches the design values. The passbands are wider than simulated, due to a reduced etch depth in between the closely spaced output waveguides.

#### C. Measurement principle

We calibrate the interrogator before the measurements. First, we record the readouts of each detector $I_i(\lambda)$ by sweeping a
The interrogator function \( \xi(\lambda) \) with a known wavelength within the full free spectral range (FSR) of the AWG. The FSR of the measured device is \( \Delta \lambda_{\text{FSR}} = 30 \) nm. Based on this data we select two photodetectors with the largest photocurrent for each wavelength. After this procedure the FSR is split into wavelength regions so that each of them can be indexed by one pair of detectors. The readout signals from these two detectors, \( I_a \) and \( I_b \), are used to calculate the interrogator function \( \xi(\lambda) = (I_a - I_b)/(I_a + I_b) \).

To reconstruct the wavelength during measurements, we use \( I_a \) and \( I_b \) from the photodetectors with maximal photocurrent. The interrogator function \( \xi(\lambda) \) together with indices \( a \) and \( b \) uniquely determines the wavelength.

The device can be used to detect multiple peaks provided they are directed to different pairs of detectors, e.g. 4/6 and 5/8 in figure 3.

### D. Resolution analysis

The resolution of the device is specified here as the RMS noise of the measured wavelength value \( \sigma_\lambda \). The error in the wavelength value \( \Delta \lambda \) can be expressed through the fluctuations \( \Delta \xi \) of the interrogator function \( \xi(\lambda) \) as \( \Delta \lambda = |d\lambda/d\xi| \Delta \xi \). Based on the known detector responses \( I_i(\lambda) \) the standard deviation \( \sigma_\xi \) of the interrogator function can be translated into the standard deviation of the measured wavelength \( \sigma_\lambda \).

To measure the resolution over the whole FSR we perform a wavelength sweep in the interval from 1540 nm to 1570 nm with a step size of \( 0.5 \) nm. At each point \( \lambda_0 \) we measure several samples of the photocurrent from all photodetectors at 4 wavelengths separated by \( \Delta \lambda_0 = 1 \) pm. In figure 5 an example of the interrogator function \( I(\lambda) \) over time for the wavelengths \( \lambda_0 \), \( \lambda_0 + 1 \) pm, \( \lambda_0 + 2 \) pm, and \( \lambda_0 + 3 \) pm is shown. The change of the readout value due to a wavelength change of 1 pm is clearly seen.

Knowing \( \Delta \lambda_2 \), we can translate the standard deviation of the interrogator function achieved from these measurements into the standard deviation of the wavelength measurement at each \( \lambda_0 \) over the whole FSR (figure 6). In the center of the FSR (1550–1560 nm) the standard deviation calculated from 40 samples at each of 4 wavelength values doesn’t exceed \( \sigma_\xi = 0.32 \) pm.

The increase of the error at lower wavelength values is due to the non-symmetric overlap of the AWG passbands in that region for this particular device, and at larger wavelength it is due to a broken photodetector with a passband peak around 1564 and 1571.5 nm. Therefore, working only in the center of the FSR with a range of 10 nm, we obtain a resolution of \( \sigma_\lambda = 0.32 \) pm.

The main cause for the noise \( \Delta \xi \) was found to be the noise of the current meter NI9207 (specification: \( 50 \) nA\( \sqrt{\text{Hz}} \), measured: \( \sim 40 \) nA\( \sqrt{\text{Hz}} \)) used to measure the photocurrents. This gives a signal-to-noise ratio of 35 to 42 dB. It can be improved by using low-noise electronics to measure photocurrent.

Assuming a spectral noise density for low-noise electronics of 0.1 nA/\( \sqrt{\text{Hz}} \) [14], the expected scanning rate for the same resolution is around 100 kHz. Additional noise, which is not noticable now but may be dominating after reducing electronic noise, can come, on one side, from the fluctuations of the fiber-to-chip coupling which causes first order mode excitation. On the other hand, the aforementioned temperature variations also lead to a slow drift of the readout signal in our measurements. Both effects can be reduced by improving the stability and thermal isolation, e.g. by packaging the device.

### V. Conclusion

We fabricated and characterised an integrated Fiber Bragg Grating interrogator with an FSR of 30 nm, 10 output channels, and a footprint of 2.5 mm\(^2\), which can be used to track wavelength shifts with a resolution of 0.32 pm over 10 nm, corresponding to a relative resolution of 0.003 %. The absolute resolution is comparable with other bulk and integrated solutions, and the relative resolution is to our knowledge the best reported for integrated interrogators.

### References


