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Keywords: arrayed waveguide grating, joint-peak demodulation method, continuous demodulation, dynamic range

Posted Date: May 9th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4305253/v1

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Additional Declarations: (Not answered)
High-Precision Continuous FBG Interrogator based on an AWG

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Abstract: Although arrayed waveguide gratings (AWGs) are widely used in fibre Bragg grating (FBG) demodulation systems, their applications in real environments have been limited due to their narrow dynamic range and inability to continuously demodulate FBGs because of the finite bandwidth of AWG channels. Here, we developed a wide-dynamic-range, high-precision, continuous-demodulation FBG interrogator utilizing a dual-input channel on-chip silicon AWG. The introduction of two input channels in the AWG allowed two spectral peaks in each channel; therefore, staggered spectral peaks were realized. A joint-peak demodulation method based on this spectrum is proposed to improve the dynamic range and demodulation precision. With the proposed structure and method, we achieved continuous interrogation with a demodulation precision of 25.58 pm and a dynamic range of 24.5 nm in the 1537.5-1565.3 nm wavelength region. The relative demodulation accuracy within the full range reaches 0.1%. The dynamic range of adjacent channels is 5.4 nm, which is approximately 4 times greater than the dynamic range of an FBG conventional demodulation system using an AWG, and the relative demodulation accuracy is 0.47%. To our knowledge, the relative demodulation accuracy is currently the highest reported. This developed interrogator, with a core size of 420 µm × 300 µm, theoretically explained and experimentally verified the possibility of the accurate measurement of an arbitrary FBG wavelength with high demodulation accuracy in the measurement range. This work achieved continuous monitoring of external temperature by FBGs and demonstrated their significant potential in expanding the application field of FBGs.

Keywords: arrayed waveguide grating; joint-peak demodulation method; continuous demodulation; dynamic range

Introduction

A fibre Bragg grating (FBG) is a new type of passive fibre sensor that has enabled a wide range of practical applications, such as aerospace and deep-sea exploration1,2, because of its strong electromagnetic interference resistance, high sensitivity, and pressure resistance advantages3,4,5,6. Traditional FBG demodulation systems have limited practical application because of their large size, complex structure and transport issues. Integrated on-chip FBG demodulation systems have attracted great interest due to their compact structure, low power consumption, and excellent performance7,8. An arrayed waveguide grating (AWG) is considered to be a promising structure for the demodulation of FBGs9,10,11, and to date, several relevant studies have been reported12,13,14,15,16. For instance, P. Cheben et al. proposed an AWG interrogator system for tilted fibre Bragg gratings (TFBGs) that can monitor two widely separated resonances17. Weng et al. demonstrated an AWG system to measure the actual wavelength of an FBG at different temperatures18. Furthermore, in the wavelength demodulation process of an FBG, the dynamic range is an important parameter. In certain measurement scenarios, such as the monitoring of a temperature field during an explosion, the temperature variation range is large. In this case, the dynamic range will have a nonnegligible
impact on the continuous demodulation of the FBG wavelength, further limiting the application conditions of FBGs in practical environments. Therefore, FBG demodulation systems with better performance should be further pursued.

According to AWG interrogator theory, there is a correlation between the dynamic range and channel bandwidth and spacing. In P. Cheben’s system\(^1\), a dense spacing of 0.18 nm between channels was set to monitor the wavelength shift of the TFBGs, and the dynamic range was 0.27 nm with a 0.14 nm bandwidth at 3 dB. Li designed an integrated AWG-based interrogator\(^2\), and the dynamic range was 0.175 nm with a 2.526 nm channel spacing. Considering the correlation between the dynamic range and the relative spectral width of FBG and AWG channels, Trita\(^3\) proposed reducing the channel spacing to increase spectral overlap, which is achieved through intentional large crosstalk between AWG channels to remove the limitation of the minimum peak spectral width of the FBG. The experimental results showed that the dynamic range was approximately 1.5 nm, and the channel spacing was 1 nm with a 1.84 nm bandwidth at 3 dB. Yuan et al. demonstrated an AWG system that increases the channel spacing to 3 nm, and the dynamic range was 1.2 nm with a 1.3 nm bandwidth at 3 dB. In the above studies, the dynamic range is still limited by the bandwidth of a single channel in the AWG and the small wavelength interval between two intersecting AWG channels\(^4\), so the dynamic range of previous demodulation methods was not large. Considering the correlation between the dynamic range and the relative spectral width of the FBG and AWG channels, a scheme for measuring the power of multiple channels is proposed to improve the dynamic range and remove the constraint of channel spacing\(^5,6\), but the peak of the FBG must overlap with several AWG channels. Dzmitry\(^7\) innovatively proposed an InP-based AWG structure combined with multimode interference (MMI), which increases the output spectrum by adding input channels, indicating that increasing the overlap of output spectra can improve the performance of demodulation systems. Based on this structure, Yuan reported an AWG-FBG demodulation system that uses two AWGs, and the dynamic range was 28 nm with a 1.3 nm bandwidth at 3 dB. Jiao\(^8\) analysed a parallel AWG demodulation system to improve the performance, and the dynamic range was 0.4 nm with channel spacings of 0.5 nm and 1 nm. However, at the edge of the measurement range, the spectral overlap significantly decreases. Therefore, it remains a challenge to improve the demodulation accuracy of the measurement band edge, increase the dynamic range of demodulation, and achieve continuous demodulation of the spectrum.

In this study, we experimentally demonstrated an on-chip silicon AWG with a dynamic range
reaching 24.5 nm. An MMI coupler was cascaded at the input end of the AWG, allowing the AWG to have two input channels and eight output channels. These structures were fabricated on silicon-on-insulator (SOI) wafers with a size of approximately 420 µm × 300 µm. The interval distance between the second input channel and the central channel was carefully designed so that the 8 output spectra generated by the second input channel were exactly in the middle of the 8 output spectra generated by the central channel, forming a targeted design of 16 staggered output spectra. The second generation of the 8 output spectra fills the gaps between the original 8 output spectra. Three adjacent spectra in the 16 spectra were grouped together, and a joint-peak demodulation method was used to increase the spectral overlap area for better demodulation performance. In this way, continuous wavelength demodulation of an FBG with a larger dynamic range over the full measurement range is achieved, with the same channel spacing and bandwidth. The experimental results show that these 16 staggered output spectra have good performance, with an insertion loss not exceeding -6.5 dB, crosstalk below -16.2 dB, and a 3 dB bandwidth of approximately 2 nm. The on-chip silicon AWG was then successfully applied to a temperature demodulation experiment of an FBG, and the wavelength demodulation precision of the FBG is as high as 25.58 pm. This is highly consistent with the results obtained by demodulation with a spectrometer. The demonstrated on-chip silicon AWG is highly promising for facilitating the development of ultracompact, large-dynamic-range, and continuously demodulated FBG wavelength demodulation systems.

Results

AWG characterization

Table 1 provides a summary of the measured AWG parameters. A compact 2× 8 AWG on a silicon-on-insulator (SOI) wafer was designed and fabricated.

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength (nm)</td>
<td>1550</td>
</tr>
<tr>
<td>d (µm)</td>
<td>2.25</td>
</tr>
<tr>
<td>Diffraction order</td>
<td>30</td>
</tr>
<tr>
<td>ΔL (µm)</td>
<td>19</td>
</tr>
<tr>
<td>Number of arrayed waveguide channels</td>
<td>25</td>
</tr>
<tr>
<td>Channel spacing (nm)</td>
<td>3</td>
</tr>
<tr>
<td>Free spectral range (nm)</td>
<td>30</td>
</tr>
<tr>
<td>Diameter of the Rowland circle (µm)</td>
<td>41</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>-2.65 (First peak)/-6.53 (Second peak)</td>
</tr>
<tr>
<td>Crosstalk (dB)</td>
<td>-22.53 (First peak)/-16.21 (Second peak)</td>
</tr>
<tr>
<td>3 dB bandwidth (nm)</td>
<td>1.95 (First peak)/2.08 (Second peak)</td>
</tr>
</tbody>
</table>

For optical characterization of the AWG transmission characteristics, first, the AWG was tested
separately without FBG reflection, as shown in Fig. 1a. A custom-made amplified spontaneous emission (ASE) source covering the wavelength range of 1400-1600 nm was used as the light source, and polarized light was obtained through a polarization controller (PC). A 1×2 MMI coupler was cascaded at the input port of the AWG, allowing the AWG to have two input channels. Then, the light was injected into the two input waveguides of the AWG on a 6-axis adjustment platform. The output optical signal was fed into the optical power meter and spectral analyser through a 1×2 splitter to ultimately obtain the output spectral characteristics of the structure. The output spectrum of the discrete 2 × 8 AWG is shown in Fig. 1b, revealing two peaks in each output waveguide and 16 spectral peaks in 8 output channels. A higher output power is defined as the first peak, while a lower output power is defined as the second peak. This configuration allowed the lower spectrum to be located in the middle of two adjacent higher-output spectra. The centre wavelengths of the output channel are 1542.1 nm (1538.1 nm), 1545.4 nm (1541.3 nm), 1548.8 nm (1544.4 nm), 1552.1 nm (1547.7 nm), 1555.4 nm (1550.7 nm), 1558.4 nm (1554.0 nm), 1561.6 nm (1557.2 nm), and 1564.7 nm (1560.3 nm), where the values in parentheses represent the second peak wavelength of each channel. However, due to the deviation between the manufactured structure and the actual refractive index from the design value, the centre wavelength of the AWG shifted. Additionally, the powers of the two peaks are slightly different due to the manufacturing deviation of the 1×2 MMI at the input port of the AWG, which results in the failure to achieve an absolute 1:1 optical power distribution. These differences will affect the demodulation accuracy of the FBG wavelength to a certain extent, but since we mainly focus on the dynamic range and methods for achieving continuous demodulation, the impact of these differences is of little concern. A microscope image of the developed chip is shown in Fig. 1c. The AWG size on the chip is 420 µm × 300 µm, and the manufacturing process flow includes e-beam direct writing (EBL) lithography, dry etching, plasma-enhanced chemical vapour deposition (PECVD), etc. The ‘Fabrication’ section describes all the details of the fabrication process.
**Fig. 1 Characterization measurements of the 2 × 8 AWG.** a Schematic of the test system. AWG-arrayed waveguide grating and PC-polarization controller. b Output spectrum of 8 output channels in the 1537.5 nm - 1565.3 nm wavelength range. c Microscopy image of the fabricated AWG.

**FBG wavelength demodulation**

For optical characterization of the AWG demodulation characteristics, the FBG was coupled to the measurement system. The FBGs were customized with centre wavelengths of 1540 nm, 1545 nm, 1550 nm, 1555 nm, and 1560 nm. The reflectivity of each FBG is approximately 60%, and the full width at 3 dB is approximately 0.8 nm. We characterized the demodulation precision and dynamic range of our on-chip silicon AWG when measuring the wavelength of the FBG, which is our main objective, using a spectrometer as a reference. During the testing process, FBGs were sequentially connected to the AWG and placed on a hot plate, with increasing temperature from 20 °C to 400 °C. The values of the spectral analyser and optical power meter were recorded, and each experiment was repeated twice to ensure the accuracy of the data.

Fig. 2 presents the experimental interrogation results for the central wavelength of the FBG. The x-axis and y-axis represent the wavelength measured by an optical spectrum analyser (OSA) and the chip, respectively. As stated, higher output power from the same input channel is defined as the first peak, denoted as H, while lower output power from the same input channel is defined as the second peak, denoted as L.
First, continuous demodulation can be realized through the joint-peak method in Fig. 2a. As shown in Fig. 2a-1 and 2a-2, the FBG wavelength is demodulated by the CH6L, CH7L, and CH8L channels, which is the traditional dual-channel demodulation method. The demodulation results in Fig. 2a-2 indicate that as the FBG moves from position FBG-I to position FBG-F, the demodulation wavelength is segmented, with a ‘gap’ of approximately 2 nm left between the two segments. This is because the demodulation range of the FBG is limited by the wavelength crossing range of adjacent channels, as shown in the shaded area in Fig. 2a-1. The appearance of a ‘gap’ is due to the inability to form cross-intervals between nonadjacent channels, which is affected by channel spacing and bandwidth, such as the ‘gap’ between CH6L and CH8L. This resulted in wavelength demodulation segmentation and a discontinuous demodulation range. To address this issue, as shown in Fig. 2a-3, the CH8H channel is added to the wavelength demodulation. The cross-interval between adjacent channels is shown in the shaded area. The cross-interval between channels increases, and the overlap area between spectra increases, thereby eliminating the ‘gap’ in wavelength demodulation. Fig. 2a-4 demonstrates that the newly introduced CH8H compensates for the missing demodulation gap, resulting in continuous demodulation wavelengths. Next, the wavelength demodulation range of adjacent channels can be increased through the joint-peak method, as shown in Fig. 2b, and the demodulation results of CH6 and CH7 are used as an example. The demodulation wavelengths in Fig. 2b-2 are displayed in three segments. The wavelength at the left end (grey) corresponds to the demodulation results of CH6L and CH7L, assuming they come from IA, with a demodulation range of approximately 1.1 nm. The wavelength at the right end (pink) corresponds to the demodulation results of CH6H and CH7H, assuming they come from the IB, with a demodulation range of approximately 1.4 nm. The intermediate demodulation wavelength (orange) is the demodulation result of CH6L and CH7H, with a demodulation range of 2.9 nm. Therefore, the demodulation range of CH6 and CH7 is 5.4 nm. Compared with traditional dual-channel demodulation methods, the demodulation range using the joint-peak demodulation method is increased by approximately 4 times.
Fig. 2 Experimental interrogation results for the central wavelength of the FBG. 

Furthermore, the demodulation accuracy can be improved through the joint-peak method, as shown in Fig. 2c. In Fig. 2c-1, the FBG wavelength is demodulated by the CH6L, CH7L, CH7H, CH8L and CH8H channels. Fig. 2c-2 shows the demodulation wavelengths of CH8L&CH7L and CH7L&CH6L, which represent the traditional dual-channel demodulation methods. The demodulation accuracy of CH8L&CH7L is 32.26 pm, and that of CH7L&CH6L is 31.80 pm. Fig. 2c-3 shows the demodulation wavelengths of CH7L&CH8H and CH8H&CH6L, representing the joint-peak demodulation method, with demodulation accuracies of 25.66 pm and 22.81 pm, respectively. Compared with the traditional dual-channel demodulation method, the demodulation accuracy of the joint-peak demodulation method is improved by approximately 9 pm. Finally, Fig. 2d shows a comparison of the demodulation accuracy of the two methods. The demodulation results obtained using the traditional demodulation method are shown in Fig. 2d-1. After linear fitting, the demodulation accuracy is 38.42 pm, and the demodulation range is discontinuous. The demodulation results obtained using the joint-peak demodulation method are shown in Fig. 2d-2. After linear fitting, the demodulation accuracy is 26.06 pm, which is a 12.36 pm increase. The high accuracy and large dynamic range of our on-chip silicon AWG were confirmed by comparing the calculated wavelength of the chip and the reference wavelength of the spectrometer. The experimental results show that a demodulation accuracy of 25.58 pm, a dynamic range of 24.5 nm, and the measurement range can be achieved by the chip, as shown in Fig. 2d-3. At the left edge of the spectrum, the demodulation accuracy gradually decreased, mainly due to the decrease in spectral overlap at the measurement band edge. In this way, an FBG wavelength interrogator with a wide dynamic range, high precision, and continuous demodulation was obtained utilizing a dual-input channel AWG.

The comparison between the advantages of the joint-peak demodulation method and those of
other current demodulation systems is provided in Table 2. The ratio between the dynamic range of adjacent channels and the demodulation accuracy is defined as the relative demodulation accuracy (Rdc) for a more intuitive comparison. Rdc represents the wavelength demodulation accuracy within the unit demodulation range, and the smaller the value is, the higher the demodulation accuracy. Although the overall demodulation accuracy of our structure is not the highest, the value of Rdc is the highest, reaching 0.47%, which means that the overall performance of our device is better. The greatest advantage of our proposed system is that it can realize continuous demodulation. To our knowledge, this is the best reported wavelength demodulation method for FBGs to date.

Table 2 Comparison of our proposed demodulation system with other current systems

<table>
<thead>
<tr>
<th>Demodulation system</th>
<th>Continuous demodulation</th>
<th>3 dB bandwidth (nm)</th>
<th>Dynamic range of adjacent channels (nm)</th>
<th>Demodulation accuracy (pm)</th>
<th>Rdc (%)</th>
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<td>/</td>
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<tr>
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<td>0.175</td>
<td>10</td>
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<tr>
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<td>1.5</td>
<td>/</td>
<td>/</td>
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<td>Ref. 28</td>
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<tr>
<td>Our proposed</td>
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<td>2.1</td>
<td>5.4</td>
<td>25.58</td>
<td>0.47</td>
</tr>
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</table>

Discussion

In contrast to conventional on-chip silicon AWG-based FBG interrogators, our developed interrogator is specialized for continuous demodulation and a wide dynamic range of FBG wavelengths. The setting of dual-input channels in the AWG allowed 16 spectra to be output from 8 output channels to form staggered spectral peaks. In this work, the second peak of each output channel participates in wavelength demodulation based on these staggered spectral peaks, yielding a continuous demodulation wavelength compared with that of a conventional FBG interrogator and solving the problem of demodulation discontinuity caused by the 'gap' in wavelength. We designed a 2 nm bandwidth at 3 dB for each output spectrum in our proposed AWG (Fig. 1b). The demodulation range of adjacent channels reached 5.4 nm using our proposed joint-peak demodulation method, which is a 4-fold improvement in the demodulation range of adjacent channels compared with that of a conventional single AWG, and the relative demodulation accuracy (Rdc) is the largest. However, due to the relatively large wavelength interval and channel bandwidth, the demodulation accuracy is slightly insufficient. Through the joint-peak demodulation method, our developed dual-input channel AWG achieved a relative demodulation accuracy (Rdc) of 0.1% within the measurement range of 24.5 nm, which means that the overall performance of our
equipment is better. We expect that our on-chip silicon AWG is suitable for temperature measurements in real environments because of its high stability against external disturbances. The spectral characteristics of our on-chip silicon AWG, including the spectral spacing and 3 dB bandwidth, are entirely determined by the AWG and are virtually insensitive to optical coupling to the fibre, ensuring the high stability during measurement. With a theoretical explanation and experimental verification, we confirmed the potential of the proposed structure for wavelength demodulation of FBGs.

**Materials and methods**

**Design of the AWG**

Fig. 3a shows the structural diagram of the AWG for implementing the method of joint-peak demodulation. The AWG structure consists of a 2 × 8 AWG and a 1 × 2 multimode interference (MMI) coupler. The MMI coupler is inserted into the input waveguide of the AWG, dividing the input port into two parts. A beam of light from the light source first enters the MMI coupler for optical power distribution, with a splitting ratio of 1:1, when the light is injected into the AWG structure. The two beams of light divided are set as IA and IB. The input channel where the IA is located is located at the centre of the input star coupler, and the input channel where the IB is located is at a certain distance $d$ from the IA. Then, in the same output channel of the AWG, both the IA and IB will output a spectral peak, meaning that the spectrum of each output channel will have two peaks. Therefore, 16 spectral peaks are transmitted from the 8 output channels of the AWG. We found that the wavelength interval between two spectral peaks in the same output channel is related to $d$. To achieve maximum overlap of the output spectrum, the output spectrum is designed specifically. The second peak from the IB is designed to be located in the middle of the first peak of adjacent channels. For ease of understanding, Fig. 3b illustrates the relationship between the output spectra from IA and IB. The red and green lines represent the spectral peaks from IA and IB, respectively. It is assumed that $\Delta \lambda$ is the wavelength interval of the output spectra of IA and IB. To achieve interleaved output spectra, the peak from the IB is designed to be located in the middle of two adjacent peaks from the IA. The channels where the three spectra are located are different. Therefore, the spectral wavelength interval of IA and IB is $1/2 \Delta \lambda$, and a joint-peak spectrum with a wavelength interval of $1/2 \Delta \lambda$ was obtained.
As shown in Fig. 3c, the position relationship between $d$ and the second peak is simulated because the second peak in each output channel comes from the IB. CH5, CH6 and CH7 are selected for illustration. The second peak of CH7 from IB is located between the first peak of CH5 and that of CH6, which is our target. The simulation results indicate that the position of the second peak spectrum gradually changes as $d$ gradually increases. According to the routing characteristics of AWG, when $d$ is a series of values, the second peak spectrum of CH7 is exactly in the middle of the first peak spectrum of CH5 and CH6. Considering the dynamic range and ease of measurement, $d$ is selected as 2.25 µm in this paper.

**Demodulation principle**

To decouple the FBG with high precision, the spectral characteristics of the AWG and FBG are further studied. There is a linear relationship between the reflective centre wavelength of the FBG and the output power ratio of the AWG channels. Thus, we need to measure only the output power to obtain the central wavelength of the FBGs with the equation (1):

$$\ln\left(\frac{P_{i+1}}{P_i}\right) = \frac{8(\ln 2)(\Delta \lambda_i - \Delta \lambda_{i+1})}{\Delta \lambda_i^2 + \Delta \lambda_{i+1}^2} \lambda_B - \frac{4(\ln 2)(\Delta \lambda_i^2 - \Delta \lambda_{i+1}^2)}{\Delta \lambda_i^2 + \Delta \lambda_{i+1}^2}$$  \hspace{1cm} (1)

where $P_i$ and $P_{i+1}$ are the output power of the channel $(i)$ and $(i + 1)$ in the AWG; $\lambda_i$ and $\lambda_{i+1}$ are the centre output wavelength of the channel $(i)$ and $(i + 1)$; $\lambda_B$ is the centre wavelength of the FBG, and
$\Delta \lambda_B$ is the bandwidth at half-peak of the FBG spectrum.

However, the dynamic range is still limited by the bandwidth of a single channel in the AWG and the small wavelength interval between two intersecting AWG channels when using the traditional AWG dual-channel demodulation method, and a large dynamic range cannot be realized, as shown in Fig. 4a and 4b. Fig. 4a shows a situation where FBG overlaps significantly with CHA1 and CHA2, with high demodulation precision, as there is no "edge overlap". As the wavelength of the FBG gradually shifts, as shown in Fig. 4b, the overlap between the FBG and CHA1 gradually decreases, and the overlap with CHA2 gradually increases. “Edge overlap” appears at the edge of CHA1, leading to a decrease in the demodulation accuracy. Moreover, due to the limitation of channel spacing, overlap between CHA3 and the FBG has not yet occurred, resulting in a ‘gap’ on the right side of the FBG, as shown by the red circle in Fig. 4b. Therefore, the problem of discontinuous demodulation arises. Scholars have adopted methods for reducing channel spacing. Although the ‘gap’ is reduced, the dynamic range also decreases, and “edge overlap” in the measurement band still exists.

![Fig. 4 Schematic of the continuous demodulation wavelength based on the joint-peak demodulation method. a, b Dual-channel demodulation of the FBG wavelength. c, d Theoretical schematic diagram of the joint-peak demodulation method for FBG wavelength demodulation.](image)

Therefore, we propose a joint-peak demodulation method to address the problems of narrow dynamic range and discontinuous demodulation. The second peak, CHB, of a certain channel from
the IB is added to perform the demodulation, as shown in Fig. 4c. Clearly, the FBG has a larger overlap area with CHA1 and CHB, and there are no edges, which means a higher output optical power and larger dynamic range compared to Fig. 4a. As the wavelength of the FBG gradually shifts, as shown in Fig. 4d, the “edge overlap” of the FBG and CHA1 also appears. Notably, FBG overlaps with CHA1, CHA2, and CHB simultaneously. The CHA2 and CHB channels can be selected to demodulate FBG wavelengths because they significantly overlap with the FBG, thereby avoiding low demodulation accuracy issues caused by “edge overlap”. Currently, the newly added second peak, CHB1, begins to overlap with the FBG; thus, the ‘gap’ is also eliminated. In this way, a high-precision, large dynamic range and continuous demodulation of the FBG wavelength is achieved.

**Fabrication**

We fabricated a series of AWGs with the parameters listed in Table 1 on a silicon-on-insulator (SOI) wafer with a top silicon layer of 220 nm and a buried oxygen layer of 2 µm. All of the AWGs were fabricated via e-beam direct writing (EBL) technology. The fabrication process is shown in Fig. 5. First, the SOI wafer is preprocessed, followed by spin coating of the negative photoresist, during which the spin coating rate and time need to be selected. Then, the AWG pattern is transferred to the SOI wafer by first EBL technology, and silicon waveguides with an etching depth of 220 nm are processed with inductively coupled plasma (ICP) technology. Afterwards, the negative photoresist is removed. Subsequently, the second spin coating process of the positive photoresist is carried out. Later, both EBL and ICP are performed to form a grating coupler with a 100 nm etching depth for IN/OUT coupling of the chip. Finally, a SiO$_2$ protection layer of 0.7 µm is grown by plasma-enhanced chemical vapour deposition (PECVD) technology to protect the AWG.

![Fig. 5 Transfer process of the AWG pattern.](image)

We selected the AWG that best matched the design parameters, as shown in Fig. 6, for detailed display under a high-powered microscope. A microscopy image of the fabricated AWG is shown in Fig. 6. Fig. 6b shows a panoramic micrograph of the AWG with a core size of 420 µm × 300 µm.
The input/output waveguide, i.e., a 450 nm wide photonic wire, is tapered to 1.5 µm to connect a star coupler, as shown in Fig. 6a. The arrayed waveguide, a 450 nm wide photonic wire, is tapered to 1 µm to reduce optical transmission loss, as shown in Fig. 6c and 6d. Fig. 6f shows a micrograph of grating couplers with straight waveguides of different lengths to reduce the loss impact of the grating coupler in the AWG. Fig. 6g and 6h show cross sections with different etching depths.

![Fig. 6 Microscopy image of the AWG.](image)

**Data availability statements**

The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy concerns.

**Acknowledgements**

This research was funded by the National Key R&D Program of China, grant number 2022YFB3205300, and the National Natural Science Foundation of China, grant number 51890884.

**Conflict of interests**

The authors declare no competing interests.

**Contributions**

Z.J. and Q.L. initiated this project and, together with K.Y., conceived the initial idea; Y.J., N.Z. and
D.X. conducted the theoretical analysis and developed the research methods; Y.J., N.Z., F.Z., and Q.M. designed the experimental architecture and conducted the simulation calculations; and Q.L., K.Y., Y.J. and F.H. analysed the results and prepared the manuscript.

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https://doi.org/10.1364/AO.51.007718


https://doi.org/10.1364/PRJ.443039


**Figure legends**

Fig. 1a-c Characterization measurements of the 2 × 8 AWG

Fig. 2a-d Experimental interrogation results for the central wavelength of the FBG.

Fig. 3a-c Target design for the AWG output spectrum.

Fig. 4a-d Schematic of the continuous demodulation wavelength based on the joint-peak demodulation method.

Fig. 5 Transfer process of the AWG pattern.
Fig. 6a-h Microscopy image of the AWG.

Tables

Table 1 Parameters of our proposed 2×8 AWG

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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<tr>
<td>Center wavelength (nm)</td>
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<td>d (μm)</td>
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<td>Diffraction order</td>
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<td>ΔL (μm)</td>
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<tr>
<td>Number of arrayed waveguide channels</td>
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<tr>
<td>Channel spacing (nm)</td>
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<tr>
<td>Free spectral range (nm)</td>
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<td>Diameter of the Rowland circle (μm)</td>
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<td>Insertion loss (dB)</td>
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<tr>
<td>Crosstalk (dB)</td>
<td>-22.53 (First peak)/-16.21 (Second peak)</td>
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<tr>
<td>3 dB bandwidth (nm)</td>
<td>1.95 (First peak)/2.08 (Second peak)</td>
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Table 2 Comparison of our proposed demodulation system with other current systems

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<th>Demodulation system</th>
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<th>Dynamic range of adjacent channels (nm)</th>
<th>Demodulation accuracy (pm)</th>
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<td>0.47</td>
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Figures
Fig. 1 Characterization measurements of the 2 × 8 AWG. a Schematic of the test system. AWG-arrayed waveguide grating and PC-polarization controller. b Output spectrum of 8 output channels in the 1537.5 nm - 1565.3 nm wavelength range. c Microscopy image of the fabricated AWG.
Fig. 2 Experimental interrogation results for the central wavelength of the FBG. a Implementation results of continuous wavelength demodulation. b Experimental results with increased dynamic range. c Experimental results for improving the demodulation accuracy of adjacent channels. d Comparison of the experimental results between the two demodulation methods.

Fig. 3 Target design for the AWG output spectrum. a Schematic diagram of the designed AWG. b Schematic diagram of the staggered output spectrum. c Simulation analysis results of $d$ and the position of the second peak.
Fig. 4 Schematic of the continuous demodulation wavelength based on the joint-peak demodulation method. a, b Dual-channel demodulation of the FBG wavelength. c, d Theoretical schematic diagram of the joint-peak demodulation method for FBG wavelength demodulation.

Fig. 5 Transfer process of the AWG pattern.
Fig. 6 Microscopy image of the AWG. a Input waveguides. b Fabricated 2 × 8 AWG. c Arrayed waveguides. d Joints of the star coupler and arrayed waveguides. e Output waveguides. f Grating couplers. g Cross section of the 220 nm etching depth. h Cross section of a 100 nm etching depth.