Optical Delay Line Employing an Arrayed Waveguide Grating in Fold-Back Configuration

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***Abstract*—A novel optical delay line (ODL) using an arrayed-waveguide grating (AWG) in fold-back configuration is proposed and experimentally demonstrated. This fold-back configuration offers crosstalk reduction and loss-imbalance as compared with previously reported loop-back AWG-based ODL. The experimental results show that different highly accurate delays can be obtained with a single AWG over a huge modulation bandwidth (2-18 GHz).**

***Index Terms*—Arrayed waveguide grating, microwave photonics, optical delay lines.**

I. Introduction

ARRAYED waveguide gratings (AWG) have been widely studied in last years because its flexibility for the construction of wavelength-dependent components. An NxN AWG is a passive optical integrated circuit that guides light into an array of waveguides that provide dispersion to separate the different wavelengths of light to different output ports, so routing functions can be performed over individual wavelengths [1]. Apart from well-known applications such as Add/Drop Multiplexers (ADM) [2], AWG-based schemes in loop-back configuration have also been proposed as wavelength-dependent optical delay lines (ODL) for applications such as phased array antennas [3], optical analog-to-digital converters [4], and optical code division multiplexing [3]. In these schemes, optical delay is obtained by means of absolute propagation delay through the specific length of optical fiber placed on the respective feedback path. The modulated optical carrier at the input port is steered by the AWG to the suitable fiber path length depending on the optical carrier wavelength, so optical time-delay is selected by switching the optical carrier wavelength.

In this letter, an optimized ODL based on an AWG fold-back configuration that offers crosstalk reduction and loss-imbalance equalization over previously reported loop-back ODL is described and experimentally demonstrated. Moreover, the proposed ODL presents the availability of obtaining easily one set of delays and their complementary one depending on the ODL input port. The experimental results show that different highly accurate delays can be obtained with a single AWG over a huge modulation bandwidth (2–18 GHz) confirming the feasibility of the proposed architecture.

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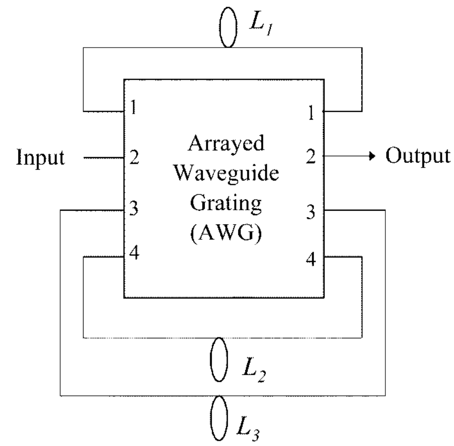

Fig. 1. Previously reported optical delay line based on an arrayed waveguide grating in a loop-back configuration.

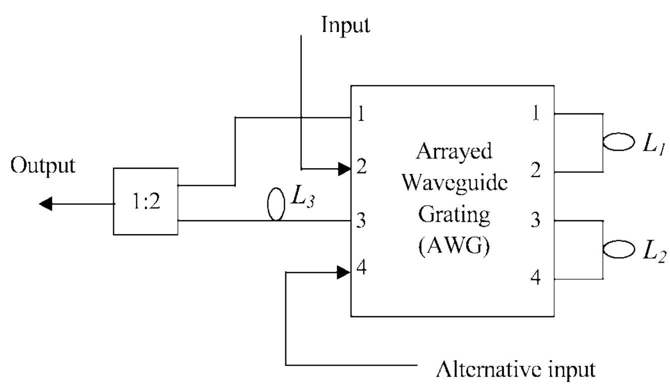

Fig. 2. Optical delay line based on an arrayed waveguide grating in a fold-back configuration.

II. Configuration

Fig. 1 depicts the previously reported loop-back AWG-based ODL. On the other hand, Fig. 2 shows the ODL with fold-back paths proposed in this work. Other fold-back configurations have been proposed ([5], [6]) but for ODL applications the arrangement depicted in Fig. 2 is preferred due to its better performance. A 4 $\times$ 4 AWG has been shown in Fig. 2 as an example configuration but the design can be properly scaled for a different number of ports. In the proposed configuration, odd output ports are connected to even output ports and the common input port of the ODL is the AWG input port 2. The AWG input port 4 may also be used to obtain the complementary delays with regard to those achieved by entering AWG input port 2. The common output port is the combination of AWG input ports 1 and 3. Optical signals impinging on common input port are routed by the AWG to one AWG output port. Then, the signals are delayed in the fold-back paths and again routed to AWG input ports 1 or 3 depending on the specific optical wavelength. Signals crossing through input port 3 are again delayed by L_3. Therefore, by using this configuration the number of optical delays with an $N \times N$ AWG is N, i.e. the same number of delays of a loop-back configuration if the direct pass is considered. Table I shows an outline of the available delays.

AWG fold-back configurations present some improvements over loop-back configurations as has been reported for ADM applications [5], [6]. In [5] the superior performance of fold-back configuration over loop-back configuration in reducing the influence of crosstalk is demonstrated. Optical crosstalk is one of the main limitations in AWG based ODL systems introducing optical amplitude and phase fluctuations which degrade the system overall performance. Instead of loop-back configuration, in fold-back ones, the crosstalk light cannot reach directly the common output port because the output is on the same side as the input. Crosstalk components are slightly coupled to the other AWG ports and these small crosstalk components are again routed through the fold-back paths to the common output port. Therefore, crosstalk is lower in these fold-back configurations than in loop-back ones.

On the other hand, regarding loss imbalance (i.e., the largest loss difference among frequency channels due to AWG nonuniform diffraction efficiency), fold-back configurations show lower channel nonuniformity than previously reported loop-back ODL. For instance, in optical beamforming applications, optical loss imbalance may become in different RF power for each antenna beam in such way that an additional power control system should be introduce in order to equalize the antenna pattern. In a fold-back configuration there is not direct path and therefore all the channels present insertion loss equal to $2 \cdot IL_{AWG}$, where IL_{AWG} is the AWG insertion loss, because of all the signals passing twice through the AWG. Unlike fold-back configurations, loop-back ones have a direct path, i.e. some wavelengths are not feedback and therefore pass through the AWG only once, so insertion losses for some channels are IL_{AWG} whereas for other are $2 \cdot IL_{AWG}$. Fig. 3(a) shows the experimental amplitude response of a 4 $\times$ 4 AWG-based loop-back ODL whereas Fig. 3(b) depicts the fold-back configuration proposed in this Letter. The loss imbalance for the loop-back configuration is equal to 8.35 dB whereas for the fold-back configuration it is reduced to 3.15 dB. Nevertheless, as can be seen in Fig. 3(b), the mean insertion loss of the ODL is increased since there is not direct pass and the optical combiner insertion loss is added to the AWG losses. However, ODL insertion losses may be highly improved using AWG with better performance than the used in this work (insertion loss equal to 7.3 dB and loss uniformity of 4 dB).

Finally, with the proposed fold-back configuration, complementary delays may be obtained depending on the input port (Table I). From Table I, it can be seen that with feedback lines of lengths equal to $L_1 = L$, $L_2 = 3L$ and $L_3 = L$ total paths lengths for λ_1 to λ_4 are $3L$, $2L$, L and $4L$. However, if the alternative input is used, total paths lengths for λ_1 to λ_4 are $2L$, $3L$, $4L$ and L respectively, which are the complementary ones to the other input delays. This feature is very useful for optical beamforming applications using heterodyne generation, where complementary delays are needed in the transmitting and receiving modes [7]. The proposed ODL in this work allows the implementation of the transmission and reception modes with the same ODL which implies an important cost reduction.

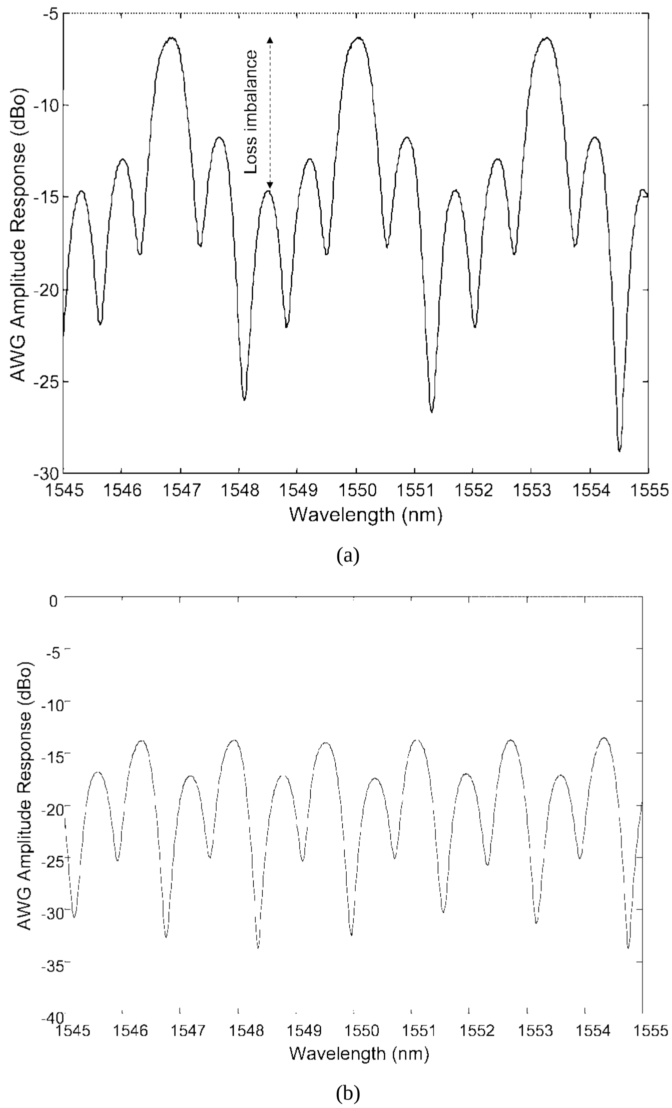

Fig. 3. Optical delay line spectral responses. (a) Loop-back configurations. (b) Fold-back configuration.

TABLE I
OUTLINE OF AVAILABLE DELAYS WITH ODL FOLD-BACK CONFIGURATION FROM FIG. 2

	λ_1	λ_2	λ_3	λ_4
Input	L_2	L_1+L_3	L_1	L_2+L_3
Alternative input	L_1+L_3	L_2	L_2+L_3	L_1

III. RESULTS AND DISCUSSION

In order to demonstrate the feasibility of the proposed ODL, the absolute delays among optical signals have been measured.

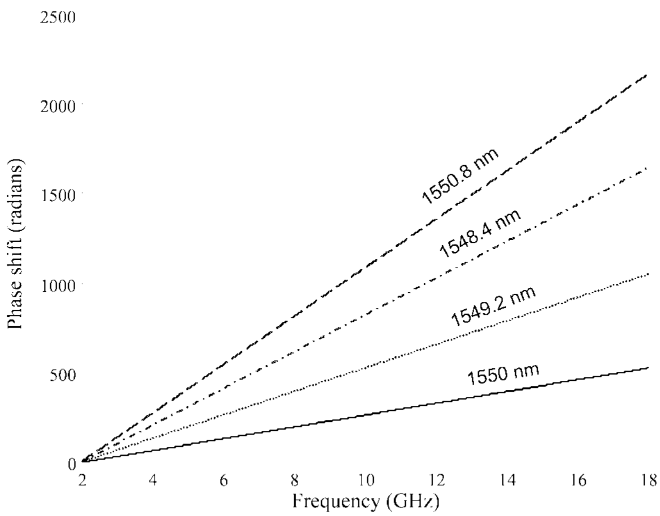

Fig. 4. Experimentally measured RF phase shift versus modulation electrical frequency. Solid line: optical path L_1. Dotted line: optical path $L_1 + L_3$. Dashed-dotted line: optical path L_2. Dashed line: optical path $L_2 + L_3$.

Optical delay has been measured through the electrical delay of one RF signal used to modulate one optical carrier. A microwave network analyzer has been used to generate one electrical signal with a frequency swept between 2 and 18 GHz (port #1). A tunable laser is employed to generate an optical carrier whose intensity is modulated by this electrical signal by means of a Mach-Zehnder electro-optical modulator. The modulated optical signal is delayed in the AWG-based ODL and further photodetected and injected to the microwave network analyzer port #2. Optical delay depends on the total length of fiber that the signal crosses, i.e. combinations of L_1, L_2, and L_3 (see Fig. 2), which also depends on the specific wavelength of the optical carrier and the AWG routing capabilities. Finally, the phase response versus frequency is measured as the phase of the S_{21} parameter. The length of the feedback lines (standard single mode fiber) used in the experiment have been $L_1 = 1.08$ m, $L_2 = 3.33$ m and $L_3 = 1.07$ m, which allows four different path lengths as stated in Table I ($L_1 = 1.08$, $L_1 + L_3 = 2.15$, $L_2 = 3.33$ and $L_2 + L_3 = 4.4$ meters, with associate delays of 5.25, 10.44, 16.20 and 21.39 ns respectively, as measured with an Optical Network Analyzer). Fig. 4 depicts the measured relative microwave phase response between 2 and 18 GHz for the four delays (combinations of L_1, L_2 and L_3) obtained with one off-the-shelf 4 $\times$ 4 AWG when the optical carrier wavelength is switched between four different values. The number of different delays is limited to the number of AWG ports which in the case of our available AWG device is $N = 4$. The delays measured from the slope of the RF phase versus frequency (Fig. 4) are 5.25, 10.54, 16.37, and 21.58 ns. Measured delays agree very well with the expected values being the maximum discrepancy of 1%, which arises from optical network analyzer delay measurement tolerance.

Else of the AWG-based ODL fold-back configuration considered in this letter there are many other potential fold-back arrangements than the one depicted in Fig. 2. For example, the fold-back arrangement based on connecting AWG output port i with $i + N/2$ port (for $i = 1$ to $N/2$), where N is the number of ports of the AWG, shows a complete loss-imbalance equalization. Such configuration is the optimum fold-back arrangement regarding loss-imbalance and due to this feature it has been proposed as ADM [5]. Nevertheless, such configuration has a smaller number of delays (only N/2) and does not present straightforward scalability which are major drawbacks when delay lines applications are aimed.

IV. Conclusions

A new fold-back AWG-based ODL, which may improve the performance of ODL's used in optical antenna beamforming, analog to digital conversion or optical code division multiplexing has been proposed and experimentally demonstrated. This configuration shows crosstalk reduction, loss-imbalance equalization and complementary delays depending on the input port as compared with other proposed AWG-based ODL. As an $N \times N$ AWG is employed, the proposed switched optical delay line offers N different delays which can be selected by tuning the wavelength of the optical carrier. The measurements carried out show extremely good performance when the delay of microwave signals in the 2–18 GHz bandwidth is considered.

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