Distributed delay-line interferometer based on a Bragg grating in transmission mode

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A novel approach for a delay line interferometer (DLI) based purely on forward Bragg scattering is proposed. We have numerically and experimentally demonstrated that a Bragg grating can deliver the functionality of a DLI in its transmission mode along a single common interfering optical path, instead of the conventional DLI implementation with two interfering optical paths. As a proof of concept, a fiber Bragg grating has been designed and fabricated, showing the desired functionality in the transmission mode of the Bragg grating. The proposed “Bragg-DLI” approach is applicable to any kind of Bragg grating technology, such as volume Bragg gratings, dielectric mirrors, silicon photonics, and other optical waveguide based Bragg structures.

**INTRODUCTION**

Delay line interferometers (DLIs), such as Mach-Zehnder or Michelson-Morley interferometers, are basic optical devices where the output optical signal is generated by interfering two replicas of the input signal, commonly generated by splitting the input signal in two different optical paths and re-combining them to generate a resulting interference signal. DLIs are used in a wide range of applications, such as the characterization of optical sources; a number of optical signal processing applications: QPSK, DPSK and PSK demodulator; and sensing of various physical and chemical parameters such as temperature, strain, refractive index, displacement curvature, inclination, or vibration [5-12].

Here we report a novel patented [13] implementation of DLIs based on a Bragg grating (BG) operated in transmission mode, with a fundamentally different physical working principle from conventional DLIs, illustrated in Fig. 1. Instead of having two physically separated optical paths for the interfering signals as showed in Fig. 1(a), in the proposed Bragg-DLI the interfering signals are simultaneously generated and interfered by forward Bragg scattering, in a single common path along the BG, represented in Fig. 1(b). As a proof of concept, we present the design and fabrication of a BG-DLI using an in-fiber implementation, concretely a phase-modulated fiber BG (FBG) in transmission mode, showing the DLI functionality of the device in numerical simulations and experimental measurements. Finally, we conclude the Letter with a summary and discussion of the results.

**Fig. 1.** Comparison of a conventional two-path DLI (free-optics implementation) (a), and a single-path Bragg-DLI (b). BS: BeamSplitter; M: Mirror.

**DESIGN AND NUMERICAL RESULTS**

An ideal DLI functionally can be expressed in the temporal domain as

$$f_{out}(t) \propto f_{in}(t) + f_{in}(t-T) \exp(j\phi)$$  \hspace{1cm} (1)

where $f_{in}(t)$ and $f_{out}(t)$ are the complex envelopes of the input and output signals respectively, $\phi$ and $T$ are the relative phase and delay between the interfering components. Equivalently in the frequency domain, we can obtain the spectral transfer function, $H(\omega) = F_{ad}(\omega) / F_{d}(\omega)$, as

$$H(\omega) \propto 2\cos(\omega T/2 - \phi/2) \exp(-j\omega T/2 - j\phi/2)$$  \hspace{1cm} (2)

, where $F_{ad}(\omega)$ and $F_{d}(\omega)$ are the Fourier transforms of $f_{ad}(t)$ and $f_{d}(t)$, respectively, $\omega$ is the base-band angular pulsation i.e. $\omega = \omega_{opt} - \omega_{opt}$ is the optical angular pulsation, $\omega_{opt}$ is the central angular frequency of the signals, and $\phi = -(1)^{1/2}$ is the imaginary unit.

BGs operating in transmission are minimum phase systems [14], therefore it is not possible to achieve a completely arbitrary response using these photonic structures. Fortunately, in our particular case, the DLI transfer function satisfies the minimum phase condition [15], $HT(\log[H(\omega)]) = \angle(H(\omega))$, where HT denotes the Hilbert transform operator, and $\angle$ denotes the phase operator, which implies that when a BG is designed for delivering the DLI spectral response amplitude in its transmission mode described in Eq. (2), the DLI spectral response phase, and therefore the temporal response described in Eq. (1), is also automatically obtained.

In principle, there is no theoretical restriction for the kind of BG technology used in the physical implementation of the BG-DLI. Here, we
have used a fiber Bragg grating (FBG) implementation operating in transmission mode [14,16-25] in order to demonstrate the proposed approach. Phase-modulated FBGs, initially proposed for virtual Gires-Tournois interferometers in reflection mode [26], have also been proposed and numerically demonstrated as an alternative feasible implementation for some specific spectral responses for pulse shaping in transmission mode [25]. The grating strength is more challenging to accurately control in the fabrication process than the grating period due to the fiber photosensitivity variability, and the non-linear relation between the writing illumination power and the corresponding fiber core refractive index modification. However, in a phase-modulated BG the grating strength remains basically uniform along most of the grating length, while the grating functionality is defined by modulating the grating period, which is much easier to accurately control in the fabrication process in practice.

In this design process we have taken into account the capabilities of our fabrication system. We have defined a grating length of 9 cm with a bandwidth of approximately 4 nm centered at \( \lambda_0 = 1550 \) nm. Following a numerical optimization process using a similar procedure to that described in [25], we have obtained a grating period function corresponding to the desired spectral function \( H(\varphi) \), where the DLI parameters have been set to \( T = 20 \) ps, and \( \varphi = 0 \). The resulting grating strength and grating period is shown in Fig. 2(a), and the corresponding data set is accessible in Data File 1 to facilitate the reproducibility of these results to other researchers. As it can be observed in Fig. 2(b), the numerically simulated spectral response in transmission of the FBG is in good agreement with the ideal response of the DLI.

In order to validate the functionality of the designed BG-DLI, we define two examples. The first one with a single pulse as an input signal to show the basic working principle, and the second one with a test sequence of pulses as an input signal that includes all possible cases of the DLI functionality. Let us define an input signal composed by a single optical pulse \( f_{in}(t) = p(t) \) for the first example, where \( p(t) \) is the complex envelope function of optical Gaussian pulses of 5 ps full width half maximum (FWHM), with central wavelength \( \lambda_0 = 2\pi c \alpha_0 = 1550 \) nm. From Eq. (1) we can deduce that the output sequence of the ideal DLI is

\[
\text{f_{out}(t)} = \sum_{k=1}^{5} d_k p(t-kT),
\]

with \( d_k \propto \{1,1\} \) (i.e. \( d_1 \propto 1 \), \( d_2 \propto 1 \)), with an intensity

\[
I_{out}(t) = |f_{out}(t)|^2 = \sum_{k=1}^{5} |d_k|^2 |p(t-kT)|^2,
\]

where we have assumed \( p(t-mT)p*(t-nT) \neq 0 \) for \( m \neq n \) (negligible pulses overlapping), and the total transmission delay is neglected. As it can be observed in Fig. 3, the output intensity and phase obtained from numerical simulations of the designed BG is in good agreement with \( I_{out}(t) \).

In the second example we define a test sequence composed of multiple optical pulses to numerically verify the BG-DLI functionality. The pulses sequence is defined by

\[
f_{in}(t) = \sum_{k=1}^{5} c_k p(t-kT),
\]

where \( c_k \propto \{1,0,1,1,-1\} \). Applying Eq. (1) we can deduce that the output sequence of the ideal DLI is given by

\[
f_{out}(t) = \sum_{k=1}^{5} d_k p(t-kT),
\]

and with an intensity

\[
I_{out}(t) = |f_{out}(t)|^2 = \sum_{k=1}^{5} |d_k|^2 |p(t-kT)|^2,
\]

where again we have assumed \( p(t-mT)p*(t-nT) \neq 0 \) for \( m \neq n \) (negligible pulses overlapping), and the total transmission delay is not taken into account. As it can be observed in Fig. 4, we can observe a good agreement the numerically obtained output intensity, and the expected \( I_{out}(t) \) previously defined.

In order to illustrate the physical generation of the interference of the BG-DLI in a common interfering path, and to emphasize the difference with conventional two interfering paths DLI approaches, we have also calculated the optical intensity distribution inside the designed BG as it propagates along the grating by using the numerical method proposed in [27] by Muriel et al. As it can be observed in Fig. 5(a) for the first example, the incident pulse is temporally separated into two components as the signal propagates along the common path, without requiring a spatial splitting in different paths at any point. For the case of the pulse sequence represented in Fig. 5(b), corresponding to the second example, the previous process is repeated for each pulse of the input sequence, and the overlapping of the resulting separated pulses leads to pulses interference (constructive or destructive) in the output signal in a distributed way along the grating.
EXPERIMENTAL RESULTS

A phase-modulated FBG has been fabricated with the previously calculated grating strength and period, using a UV laser direct-writing system developed at Aston University, where the grating is created pitch-by-pitch, and the coupling coefficient profile and the varied period are realized by controlling the ON/OFF of an acoustic optical modulator and moving the phase mask/fiber. A hydrogen-loaded photosensitive fiber, later stabilized by annealing at 80°C for 60 h after the fabrication of the grating, was used in the process. The fabricated FBG has been characterized using a broad spectrum light source as excitation, and measuring the output spectrum of the FBG in transmission, which is shown in Fig. 6(a) compared to the ideal DLI interferometer. The corresponding spectral phase is also shown in Fig. 6(b), which has been numerically recovered from the previous spectral intensity measurement by using the Hilbert transform relations of the transmission spectral response amplitude/phase [14], a method reported as more robust than measurement by spectral interferometry in [28]. As it can be observed, the errors in the fabrication process affects as a distortion of the FBG spectral response amplitude and phase observed in Fig. 6 (a) and (b), as it is described in [29]. However, it is worth noting that the transmission mode phase response is less sensitive to grating-fabrication errors than in reflection mode [14,30]. In any case, a reasonably good agreement between ideal and fabricated DLI response can be observed in the bandwidth of interest for both amplitude and phase spectral response.

The response to optical pulses in transmission mode of the fabricated FBG has been characterized by using a pulsed laser based on an Erbium gain based single-walled carbon nanotube (CNT) passively-mode-locked fiber laser as excitation, where the spectrum of these pulsed laser input and the corresponding FBG-DLI output is also showed in Fig. 6(a). The input and output signals has been also characterized in temporal domain by using an intensity auto-correlator, where the autocorrelation of input and output is showed in Fig. 6(b). As it can be observed, the autocorrelation intensity indicates an output signal composed by a double pulse with a relative delay of approximately 20 ps in the output signal, matching the designed DLI functionality.

Regarding the environmental sensitivity/tunability properties of the fabricated DLI-FBG, we have verified that similar to other FBGs [31-33] the central Bragg wavelength can be shifted by the application of either temperature or strain variation while the spectral response remains approximately undistorted. In Fig. 7, dependence to temperature and strain is showed, where we obtained a spectral shift of 9.81×10⁻⁵ nm/°C for temperature, and 1.14×10⁻⁴ nm/°C for strain. Taking into account that a shift in wavelength of 0.8014 nm (free spectral range) corresponds to a variation of 2π in ϕ, we can easily deduce the dependence of ϕ on temperature to be 76.9 mrad/°C, and on strain to be 89 mrad/µε. These values are significantly smaller than the typically very high sensitive two-path DLIs, where a relative variation of optical paths equivalent to a wavelength produces a variation of 2π in ϕ

A proper package is needed when a reduced environmental sensitivity of an optical device is required. An athermal packaged FBG reported in [34] can reduce the thermal sensitivity to a value of 0.41×10⁻⁴ nm/°C, which corresponds to a shift in ϕ of 3.2 mrad/°C. Most recent commercial packaging report an even lower thermal sensitivity of < 0.1 nm (OQuest, part number 91000223-063), in a temperature range from -5 °C to +70 °C, which correspond to maximum DLI relative phase variation ϕ<78.4 mrad in this temperature range of 75 °C. In [35] a packaged all fiber MZIs with same delay amount as our fabricated DLI of 20 ps, is reported with a thermal shift in ϕ of 91.9 mrad/°C, which is significantly higher than that of a packaged FBG (even also higher when compared to the unpackaged FBG).

These properties suggest a possible use of proposed BG-DLI when low sensitivity is desired, such as signal processing applications where environmental perturbations are undesirable, or high range sensing applications, possibly combined with a more sensitive sensor of smaller range.
CONCLUSION AND DISCUSSION

We have proposed and demonstrated a novel implementation of a DL1 based on a Bragg resonant structure in transmission mode, with a fundamental working principle radically different to that of conventional two-interfering paths DLIs. As a proof of concept, an optical fiber implementation of a Bragg-DL1 using a phase-modulated FBG was designed and fabricated. In the numerical simulations we have shown the desired DL1 functionality of the designed FBG, and for illustrative purpose the optical intensity distribution inside the Bragg grating has also been calculated, showing how the forward Bragg scattering generates a single common path interference in a distributed way along the Bragg grating. An FBG has been fabricated according to the design parameters, and the temporal and spectral characterization shows a good agreement with the desired DL1 functionality. It is worth noting that in this Letter we also report the first experimental demonstration of a phase-modulated FBG for the synthesis of a specific spectral response in transmission mode, which were proposed but only numerically demonstrated in [25] for some pulse shaping applications.

Sensitivity to environmental changes is typically very high in conventional two path based DLIs, where any relative variation of the effective optical paths of the interfering components in the order of a fraction of a wavelength produces a significant variation of the response, making them very suitable for sensing applications of small perturbations. Additionally, in-fiber implementation of two-paths DLIs, any relative difference in the polarization state in the DL1 paths will affect to the performance.

In our case, the proposed Bragg-DL1 have a common interfering path, showing a higher robustness to environmental changes, which may be more indicated for applications where a well-controlled DL1 operation is desired, or for sensing a higher range of variations of environmental variables. The central wavelength can be accurately tuned by strain or temperature similarly to conventional FBG, while the whole response remains basically undistorted. It is worth noting that only \( \phi \) can be tuned in practice in the FBG-DL1, while the relative delay \( T \) remains approximately constant. It is worth noting that this limitation also applies to most conventional waveguide MZIs, where the induced variations in the optical path by application of temperature in one of the MZ arms only affects significantly to the relative phase, but very marginally to the relative delay.

In principle, this approach can be implemented in any kind of Bragg grating technology, such as volume Bragg gratings, dielectric mirrors, silicon photonics, or other optical waveguide technologies based Bragg structures, introducing an alternative for the physical implementation DLIs based in a common optical interfering path.

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**SUPPLEMENTARY MATERIALS**

Dataset 1. https://doi.org/10.5281/zenodo.167590

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**Visualization 1.** https://doi.org/10.5281/zenodo.167588