

32-Channel Thin-Film Lithium Niobate Optical Power Distribution Network for Spaceborne Fibre Bragg Grating Sensing

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ABSTRACT

Fibre Bragg grating (FBG) sensors are attractive for distributed temperature and strain monitoring in space applications due to their passive operation, low mass, and multiplexing capability. This work presents a 32-channel thin-film lithium niobate (TFLN) optical power distribution network (OPDN) as a compact integrated alternative to conventional fibre-based splitters for tunable laser FBG interrogation. The OPDN consists of a five-stage cascaded 1×2 multimode interference (MMI) splitting tree fabricated on a 5 mm × 5 mm TFLN chip. Experimental characterisation of the packaged device over 1530–1570 nm demonstrates broadband operation across all 32 channels, with a mean transmission of approximately −24.3 dB at 1550 nm and spectral ripple below 2.5 dB for all channels. The demonstrated device provides a compact and scalable optical distribution stage for multi-branch FBG sensing, with potential application in future spaceborne temperature and strain monitoring systems.

Keywords: thin-film lithium niobate, fibre Bragg grating, OPDN, photonic integrated circuit, distributed fibre sensing, tunable laser interrogation, spaceborne sensing, structural health monitoring.

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1. INTRODUCTION

Photonic integrated circuits (PICs) have emerged as a key enabling technology for next-generation optical sensing systems by integrating multiple optical functions onto a single chip. Compared to systems based on discrete components, PICs can significantly reduce system footprint, weight, power consumption, optical alignment requirements, and packaging complexity, while improving robustness and reliability. These advantages are particularly important for aerospace and space applications, where stringent constraints on size, weight, power consumption, and environmental robustness must be satisfied [1]. Among the available photonic integration platforms, TFLN has recently attracted significant attention due to its combination of low optical propagation loss, wide optical transparency window, strong electro-optic response, and compatibility with compact integrated photonic components [2]. These properties make TFLN a promising platform for low-loss, scalable photonic circuits in optical sensing.

Among optical sensing technologies, FBG sensors have attracted considerable interest due to their passive operation, immunity to electromagnetic interference, lightweight optical fibre infrastructure, corrosion resistance, and capability to multiplex multiple sensing points along a single optical fibre [3] – [5]. These characteristics make FBG sensors particularly suitable for aerospace and space applications, including distributed temperature and strain monitoring, structural health monitoring of composite panels, thermal monitoring of spacecraft components, monitoring of deployable structures, and propulsion or cryogenic tank health monitoring [6], [7]. To exploit these advantages while reducing the size and complexity of the associated instrumentation, significant research has focused on developing compact photonic-integrated FBG interrogators capable of replacing bulky laboratory instrumentation. As summarised by Marin et al. [3], several interrogation techniques have been investigated using photonic integrated circuits, including Arrayed Waveguide Gratings (AWGs), Mach–Zehnder Interferometers (MZIs), Micro-ring Resonators (MRRs), linear edge filters, Fabry–Perot filters, and tunable laser interrogation. Among these techniques, AWG-based interrogators are the most mature integrated solution because they provide simultaneous wavelength demultiplexing, parallel interrogation

of multiple FBG sensors, compact implementation, and high wavelength accuracy. Li et al. demonstrated the first monolithically integrated SOI AWG-photodiode interrogator with approximately 1 pm wavelength resolution and 6.79 pm interrogation accuracy [8]. Chen et al. further reported a fully integrated AWG interrogator covering both the C- and L-bands, achieving an 80 nm interrogation range, <2 pm wavelength accuracy, and simultaneous interrogation of 20 FBG sensors [9]. More recently, Jiao et al. demonstrated a silicon AWG interrogator with 0.28 pm wavelength resolution, 10 kHz interrogation speed, 0.03 °C temperature resolution, and reliable operation under harsh thermal environments, illustrating the excellent performance achievable using AWG-based photonic integrated interrogators [10].

Mach–Zehnder Interferometer (MZI)-based interrogators constitute another important class of integrated FBG readout units. Instead of directly separating wavelengths, MZIs convert wavelength shifts into optical phase variations, enabling high interrogation sensitivity and dynamic response. Marin et al. experimentally demonstrated an SOI integrated unbalanced MZI interrogator employing active phase demodulation, achieving a dynamic strain resolution of 72.3 nε/√Hz [11]. Passive and active MZI interrogation techniques have also demonstrated multiplexing capability while maintaining compact integrated implementations [3]. MRR-based interrogators have also attracted considerable attention owing to their compact footprint, high wavelength selectivity, and compatibility with dense photonic integration. Their resonance wavelength can be thermally tuned, enabling compact wavelength-interrogation systems, although their multiplexing capability and sensitivity to resonance drift must be carefully considered. Alternative interrogation techniques based on linear edge filters, Fabry–Perot filters, and tunable laser scanning have also been investigated [3]. Linear edge filters provide simple wavelength-to-intensity conversion, whereas Fabry–Perot filters can provide high spectral selectivity.

Tunable laser interrogation is particularly attractive because wavelength scanning can be combined with direct photodetection and high-precision wavelength referencing. Ibrahim et al. demonstrated a tunable laser-based interrogator operating at sweep rates of up to 8 kHz, with a dynamic range of approximately 120 dB and wavelength precision below 100 fm. The same work also demonstrated the feasibility of replacing several discrete optical components with an InP PIC [12]. Despite significant advances in photonic integrated FBG interrogators, conventional tunable laser-based interrogation systems still rely on discrete fibre-based optical splitters to distribute optical power from a single laser source to multiple FBG sensing heads. Although mature and widely adopted, these splitters increase the system footprint, fibre routing complexity, packaging effort, and overall mass, while introducing numerous fibre interconnections that may reduce mechanical robustness. Replacing the discrete splitter with an integrated OPDN provides a compact, lightweight, and scalable alternative, particularly attractive for spaceborne distributed sensing systems. In this work, we present a 32-channel TFLN OPDN as the optical front-end of a tunable laser-based FBG interrogation system for distributed temperature and strain sensing.

2. TUNABLE LASER-BASED MULTI-CHANNEL FBG INTERROGATION ARCHITECTURE

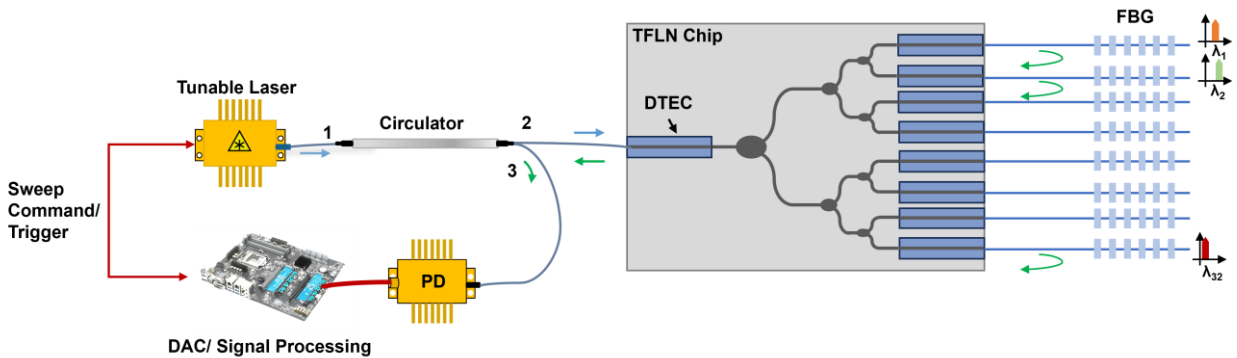


Figure 1. Proposed 32-channel TFLN OPDN integrated within a conventional tunable laser FBG interrogation system. TFLN: Thin-Film Lithium Niobate; OPDN: Optical Power Distribution Network; FBG: Fibre Bragg Grating; DTEC: Double Tapered Edge Coupler; PD: Photodetector; DAQ: Data Acquisition.

Figure 1 illustrates the proposed distributed FBG sensing architecture based on a 32-channel TFLN OPDN. The system employs a conventional tunable laser interrogation scheme, where optical power from a single tunable laser is launched into the PIC through a double tapered edge coupler (DTEC) via an optical circulator. The OPDN uniformly distributes

the optical signal among 32 output channels, each providing an independent sensing branch. Each output branch can accommodate one or multiple FBG sensors connected in series, with each FBG designed to operate at a distinct Bragg wavelength. This wavelength-division multiplexing (WDM) capability significantly increases the total number of sensing points without requiring additional optical distribution hardware, enabling highly scalable distributed sensing networks. Consequently, the overall sensing capacity depends on the wavelength bandwidth of the interrogation system and the spectral spacing between adjacent FBGs.

During operation, the tunable laser continuously sweeps across the interrogation wavelength range. Each FBG reflects optical power only when the instantaneous laser wavelength coincides with its Bragg wavelength, while the remaining optical power continues to propagate towards subsequent FBGs connected along the same branch. The reflected optical signals are routed back through the optical circulator and detected using a single photodetector (PD). The photodetector records the reflected optical power as a function of time, while the data acquisition (DAQ) unit synchronises the laser sweep and converts the detected reflection peaks into their corresponding Bragg wavelengths using the calibrated wavelength–time relationship of the tunable laser. Changes in the measured Bragg wavelengths are subsequently translated into temperature or strain according to the sensitivity of each FBG.

Unlike conventional distributed FBG sensing systems, which typically employ discrete fibre-based optical splitters to distribute optical power, the proposed architecture integrates the entire OPDN onto a compact TFLN photonic integrated circuit. This approach reduces the number of discrete optical components and fibre interconnections, decreases the system footprint and mass, simplifies packaging, and improves mechanical robustness. Furthermore, the high channel uniformity achieved by the OPDN ensures balanced optical power delivery across all sensing branches, improving measurement consistency and supporting scalable multi-point sensing for future spaceborne monitoring applications.

3. DESIGN OF THE 32-CHANNEL TFLN OPTICAL POWER DISTRIBUTION NETWORK

The proposed OPDN is implemented on a TFLN photonic integrated circuit and is based on a five-stage cascaded splitting tree. The network consists of successive 1×2 multimode interference (MMI) couplers that progressively divide the optical power from a single input into 32 output channels. The passive architecture does not incorporate active phase-control elements, allowing the device to operate as a broadband optical power distribution stage for the distributed FBG sensing architecture described in Section 2. The five-stage topology provides a compact and symmetric approach for

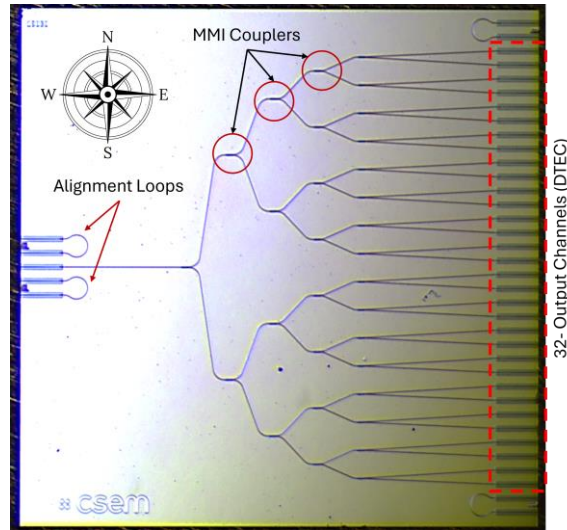


Figure 2. Microscope image of the fabricated 32-channel TFLN OPDN, including the five-stage MMI splitting tree, alignment-loop structures, and the 32 output waveguides.

distributing the input optical signal among the 32 sensing branches. Ideally, equal splitting through five consecutive stages corresponds to a power division of $1/32$ at each output, equivalent to an ideal splitting loss of approximately 15.05 dB per channel, excluding propagation, coupling, and excess losses. The complete OPDN was fabricated on a compact 5 mm $\times$ 5 mm TFLN chip. Figure 2 shows a microscope image of the fabricated TFLN OPDN, including the five-stage MMI splitting tree, alignment-loop structures, and the 32 output waveguides.

Optical coupling between the external fibres and the TFLN waveguides is achieved using DTEC at the input and output facets. The DTECs are designed to improve the mode-field overlap between the optical fibre and the on-chip waveguide, thereby reducing the coupling loss at the chip interfaces. In addition, dedicated alignment-loop structures are incorporated at both sides of the chip. These structures operate together with the V-grooves of the fibre arrays and facilitate accurate fibre-to-chip alignment during packaging and experimental characterisation. For the proposed FBG sensing application, the 32 outputs of the OPDN provide 32 independent optical sensing branches. Each branch can be connected either to a single FBG or to multiple wavelength-multiplexed FBG sensors connected in series. Consequently, the integrated OPDN provides the optical distribution functionality required to extend a single tunable laser interrogation path to a large number of spatially distributed sensing locations.

4. EXPERIMENTAL CHARACTERIZATION OF THE 32-CHANNEL TFLN OPDN

Prior to the experimental characterisation, the fabricated 32-channel TFLN OPDN was packaged with fibre arrays attached to the input and output facets, as shown in Figure 3. The fibre arrays provide optical access to the 32 output channels and to the dedicated alignment-loop structures incorporated on the chip. The packaged device was subsequently characterised over the 1530–1570 nm wavelength range to evaluate the fibre-to-chip coupling performance, insertion loss, channel-to-channel uniformity, and spectral behaviour of the OPDN. The transmission characteristics were measured using a Brillouin optical spectrum analyser (BOSA Series 6, Aragon Photonics).

Prior to the characterisation of the complete OPDN, the dedicated alignment-loop structures were measured to evaluate the coupling performance of the chip interfaces and estimate the contribution of the DTECs to the total insertion loss. The measured transmission responses of the four alignment loops are shown in Figure 4. The responses remain relatively smooth across the 1530–1570 nm wavelength range, indicating stable fibre-to-chip coupling over the spectral range of interest. Three of the measured loops exhibit transmission levels of approximately -6 to -7 dB, while one of the east-side loops shows approximately 1–2 dB higher loss. From these measurements, the coupling loss is estimated to be approximately 3–3.5 dB per facet for the majority of the interfaces. The observed differences between the loops can be attributed to fibre positioning, local facet quality, packaging tolerances, and fabrication non-uniformities.

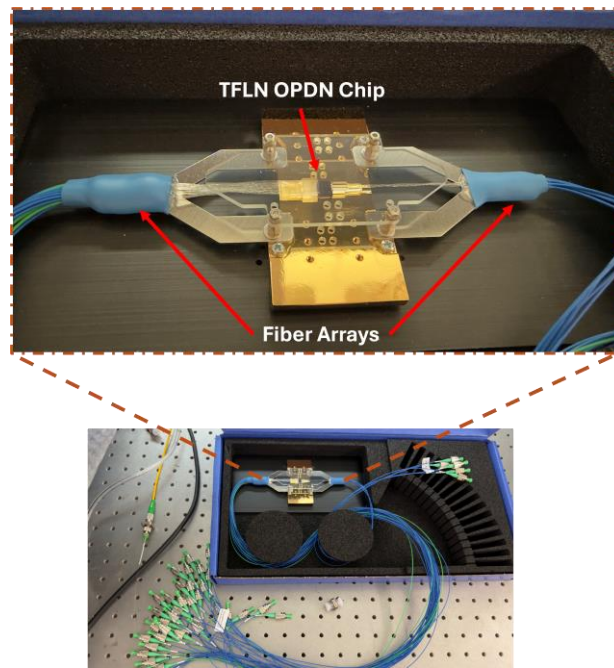


Figure 3. Packaged passive 5-stage OPDN chip with mounted fibre arrays.

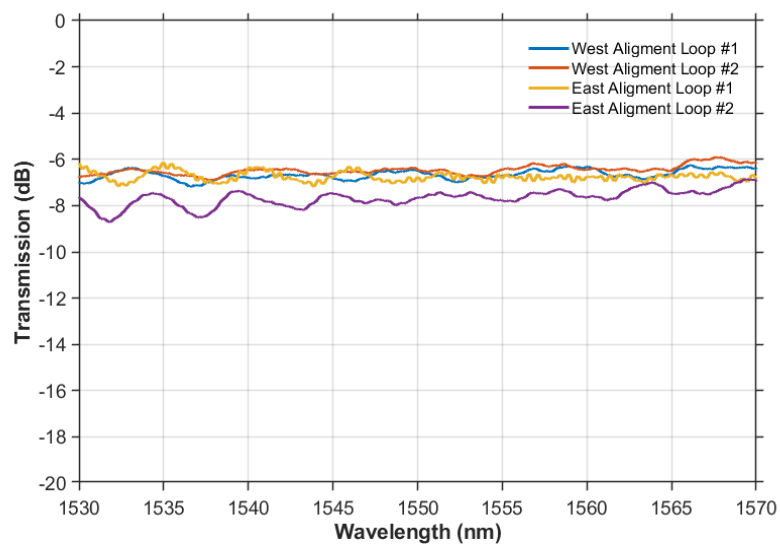


Figure 4. Measured transmission spectra of the four alignment loops over the 1530-1570 nm wavelength range.

Following the coupling characterisation, the transmission of all 32 OPDN output channels was measured across the same wavelength range. Figure 5 presents the mean transmission of the 32 channels together with the corresponding channel-to-channel spread. The mean transmission remains relatively stable over the measured spectral range, demonstrating broadband operation of the passive splitting network around 1550 nm. The bounded channel-to-channel spread indicates that the optical power is distributed with reasonable uniformity among the 32 output branches, although some variation between individual channels is observed. These variations can arise from small fabrication non-uniformities within the cascaded splitter network as well as residual differences in fibre-to-chip alignment.

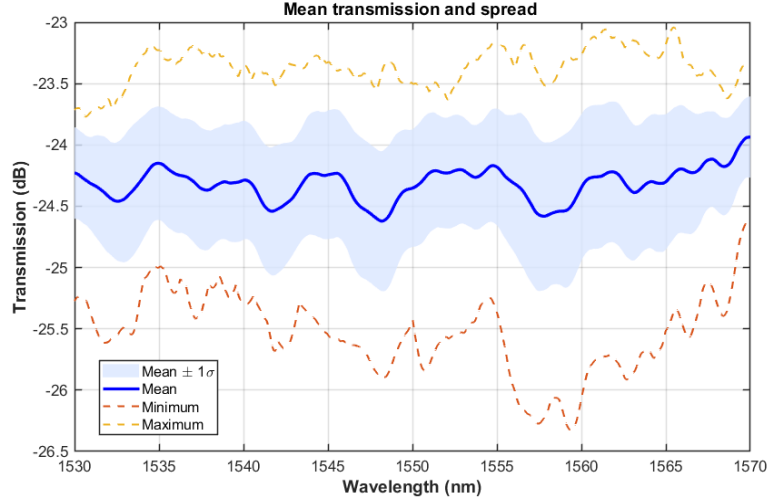
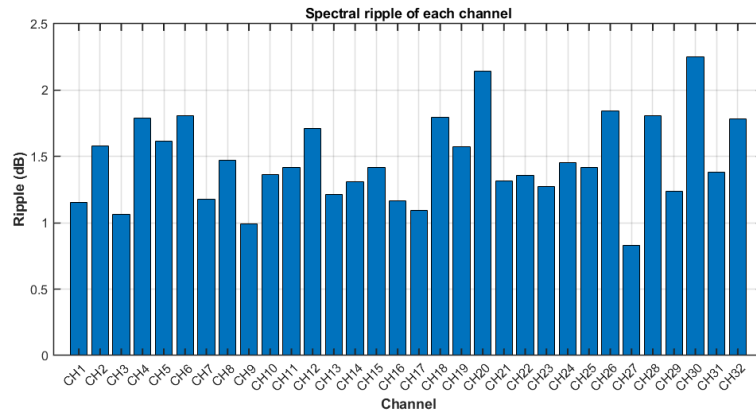
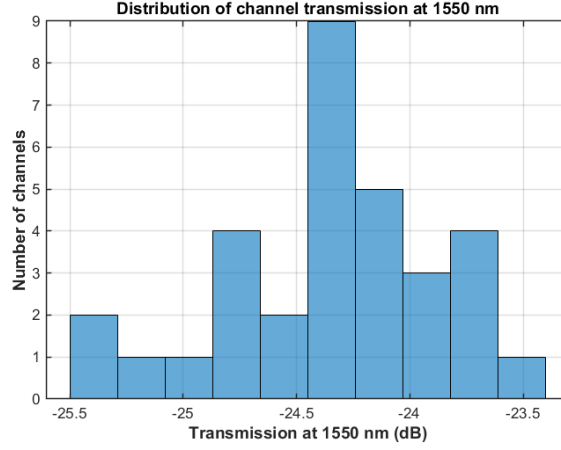


Figure 5. Mean measured transmission of the 32 OPDN output channels as a function of wavelength, including the channel-to-channel spread.

The spectral stability of the individual output channels was further evaluated by calculating the transmission ripple across the measured wavelength range. As shown in Figure 6(a), the spectral ripple remains below approximately 2.5 dB for all 32 channels, with the majority of the channels exhibiting values between 1 and 2 dB. This relatively low wavelength-dependent variation is particularly relevant to the proposed tunable laser FBG interrogation architecture, since the OPDN should maintain a consistent power distribution as the laser is swept across the operating wavelength range. The larger ripple observed for a limited number of channels may originate from weak optical reflections, small differences in optical path length, or fabrication-induced variations within the passive network.



(a)



(b)

Figure 6. Measured performance of the 32-channel TFLN OPDN: (a) spectral ripple of each output channel over the 1530–1570 nm wavelength range and (b) distribution of the channel transmission at 1550 nm.

The channel-to-channel transmission distribution at 1550 nm is presented in Figure 6(b). The measured output levels are centred around approximately -24.3 dB, with most channels concentrated within a relatively narrow transmission range and no strongly isolated outlier channels. This distribution demonstrates that the fabricated OPDN provides reasonably uniform optical power delivery across the 32 output branches. For the proposed FBG sensing architecture, this characteristic is important for providing comparable optical power to the different sensing branches and, consequently, maintaining similar available reflected signal levels across the distributed sensor network.

The measured insertion loss can be separated into the fundamental splitting loss, fibre-to-chip coupling loss, and excess loss introduced by the cascaded MMI network. For an ideal power divider, the theoretical splitting loss is 15.05 dB. From the alignment-loop measurements, the fibre-to-chip coupling loss is estimated to be approximately 3.5 dB per facet, corresponding to approximately 7 dB for the complete input-to-output optical path. After accounting for the ideal splitting loss and the estimated coupling losses, the total excess loss associated with the five-stage MMI network is approximately 2.5 dB, corresponding to an average excess loss of approximately 0.5 dB per MMI stage. Minor additional contributions from routing waveguides, bends, and measurement uncertainty may also be included in this estimate. Overall, the measurements demonstrate broadband optical power distribution across 32 parallel output channels, with moderate channel-to-channel variation and limited spectral ripple over the 1530–1570 nm wavelength range. These characteristics support the use of the fabricated TFLN OPDN as the optical distribution stage of the tunable laser based FBG sensing architecture presented in Figure 1.

5. CONCLUSIONS

A 32-channel TFLN OPDN has been demonstrated as an integrated optical distribution stage for tunable laser based FBG sensing. The proposed approach replaces a conventional discrete fibre-based splitting network with a compact photonic integrated circuit, enabling a single optical source to address 32 independent sensing branches. Each branch can additionally accommodate multiple wavelength-multiplexed FBGs connected in series, providing a scalable architecture for distributed temperature and strain sensing.

The OPDN was implemented on a $5\text{ mm} \times 5\text{ mm}$ TFLN chip using a five-stage binary splitting tree based on cascaded 1×2 MMI couplers, with DTECs and dedicated alignment structures incorporated for fibre-array coupling and packaging. Experimental characterisation of the packaged device over the 1530–1570 nm wavelength range demonstrated broadband operation across all 32 output channels. The measured transmission at 1550 nm was centred around approximately -24.3 dB, while the spectral ripple remained below approximately 2.5 dB for all channels, with the majority exhibiting values between 1 and 2 dB.

The measured loss is dominated by the fundamental 15.05 dB 1×32 splitting loss and approximately 7 dB fibre-to-chip coupling loss, while the excess loss attributed to the five-stage MMI network is estimated at approximately 2.5 dB, corresponding to about 0.5 dB per splitting stage. These results demonstrate that the integrated TFLN OPDN can provide broadband and uniform optical power distribution to a large number of parallel sensing branches, supporting its use as a compact optical front-end for scalable FBG interrogation systems. Future work will focus on system-level validation with FBG sensors for temperature and strain measurements and on assessing the packaged device under environmental conditions relevant to spaceborne operation.

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