Characterization of Heterogeneously Integrated Periodically-Polled Lithium Niobate using Optical Frequency-Domain Reflectometry

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ABSTRACT

Photonic integrated periodically poled lithium niobate (PPLN) has emerged as one of the most promising photonic devices for both classical and quantum applications, thanks to its efficient nonlinear optical processing capabilities. However, the characterization of such integrated device has been barely studied, particularly regarding adverse reflection properties arising from coupling facets. In this paper, we present the successful integration of a wavelength conversion module using a PPLN on a thin film lithium niobate by integrating two different platform technologies: silicon nitride and lithium niobate. The module features 5 mm-long periodically poled waveguides on lithium niobate-on-insulator, designed for wavelength up-conversion from 1560 nm to 780 nm via second harmonic generation. The PPLN waveguides are packaged with silicon nitride interposers for edge coupling mode size conversion to an optical fiber array. To characterize reflection profiles along the fabricated device, we employ an optical frequency-domain reflectometry (OFDR), operating at 1560 nm with a spatial resolution of 1.5 mm in air at 100 Hz measurement rate. The sensing system enables detailed analysis of reflections potentially caused by refractive index mismatching at the coupling facets and by micro-structured periodic domain inversion within the PPLN. Our experimental results clearly reveal three strong reflections along the device structure, corresponding to the optical fiber array, the silicon nitride interposer, and the PPLN. The reflectivity at each facet is measured to be -27.8 dB, -31.7 dB, -21.4 dB, respectively, demonstrating the ability of OFDR for the characterization of the photonic integrated device packaging.

Keywords: Distributed optical fiber sensing, light scattering, optical fibers, optical frequency-domain reflectometry, periodically poled lithium niobate, wavelength conversion module, hybrid photonic integration

1. INTRODUCTION

Today photonic integrated circuits (PICs) have the potential to revolutionize the photonics in existing applications in various research fields such as metrology, sensing, biosensing and microwave photonics. Moreover, the PIC technology is paving the way to adopt photonic solutions in emerging areas with huge interest such as neuromorphic computing, quantum communications and quantum computing [1]. The next generation of PICs is extensively focused on the optimization of hybrid solutions, by integrating different PIC platforms such as silicon nitride, GaAs, InP and lithium niobate. This approach aims to develop high performance photonic devices that offer efficient emission, modulation, nonlinear processing and detection of light while ensuring the wideband operation and integration robustness. The thin film lithium niobate has emerged as one of the most promising photonic integration platforms, owing to its outstanding electro-optic and nonlinear optical properties, which enables the development of multifunctional PIC components. A key feature of lithium niobate is its large second-order nonlinearity ($\chi^{(2)}$), which is fundamental to various physical mechanisms such as second-harmonic generation, sum- and difference-frequency generation and spontaneous parametric down-conversion, all of which are crucial for efficient optical wavelength conversion [2,3]. For this reason, thin-film periodically poled lithium niobate (TF-PPLN) devices are gaining significant attention for their effectiveness in efficient wavelength conversion process across both classical and quantum applications.

In this study, we demonstrate the successful integration of thin film PPLN with a silicon nitride platform, specifically the TripleX interposers supplied by LioniX International, developed within the framework of the HORIZON EUROPE project LOLIPOP (grant agreement No. 101070441). The PPLN waveguides are edge-coupled to two 5 mm long silicon nitride

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chips. To accurately assess the quality of this hybrid integration, we analyzed the reflection profile along the fabricated device using the standard optical frequency-domain reflectometry (OFDR), a technique demonstrated in the previous work [4]. The system operates at 1560 nm with a spatial resolution of 1.5 mm in air at 100 Hz measurement rate. This sensing system provides detailed insight into reflections that may arise from the effective index mismatches at the coupling interfaces and from the micro-structured periodic domain inversion within the PPLN. Our experimental results disclose three distinct reflection peaks along the device, possibly corresponding to the facets of the optical fiber array, the silicon nitride interposer and the PPLN waveguide. The measured reflectivity at these facets is -27.8 dB, -31.7 dB, -21.4 dB, respectively. These findings essentially highlight the significant potential of OFDR as a powerful tool for characterizing hybrid integrated of photonic circuits, offering a detailed and accurate method to assess the integration performances.

2. HYBRID INTEGRATION TO FABRICATE WAVELENGTH CONVERSION MODULE

The wavelength conversion module consists of an input fiber array using 1550 nm PM fiber, an input spot-size converter built on the TriPleX platform [5] and optimized for 1550 nm, the PPLN waveguide chip, a TriPleX output spot-size converter optimized for 780 nm, and an output fiber array using 780 nm PM fibers. A detailed picture is shown in Figure 1. Both spot-size converter chips are designed to adapt the mode between the respective fiber array and the PPLN waveguide. They are 5 mm long and the effective index on the majority of this chip is 1.52. The PPLN chip is fabricated on a thin-film lithium niobate on insulator (TFLN) wafer in a multi-project wafer (MPW) run using a wafer-scale process [6]. The layer stack consists of a 4.7 µm bottom SiO_2 cladding, a 600 nm thick lithium niobate layer which is etched by 200 nm, a metal layer for the poling of the lithium niobate, and a 4.7 µm top SiO_2 cladding layer. Since the lithium niobate waveguide is poled at the end of the wafer processing, only the slab region gets poled and contributes to the mode overlap [7]. Thus, we use a shallow etched waveguide to maximize the mode overlap and the conversion efficiency. The modes are shown in Figure 2. The PPLN is 5 mm long and the measured normalized conversion efficiency is 380 %/W/cm². The effective index at 1550 nm is 1.92 and the poling period is 4.47 µm.

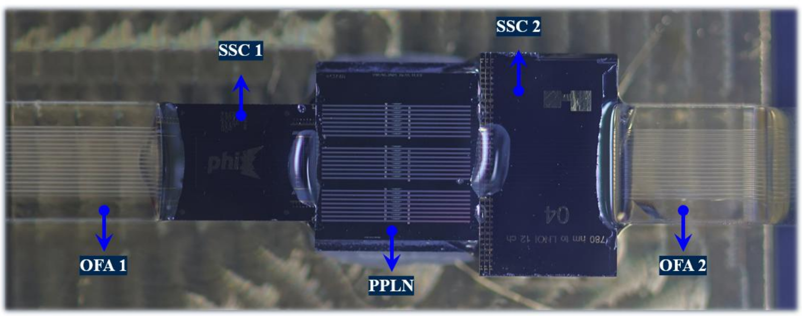
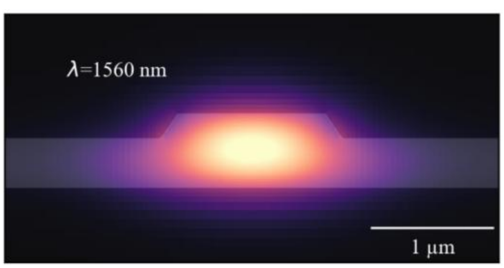


Figure 1: Photo of the fabricated PPLN using the hybrid integration between silicon nitride and lithium niobate platform technologies. OFA: optical fiber array. SSC: spot size convertor. PPLN: periodically poled lithium niobate.



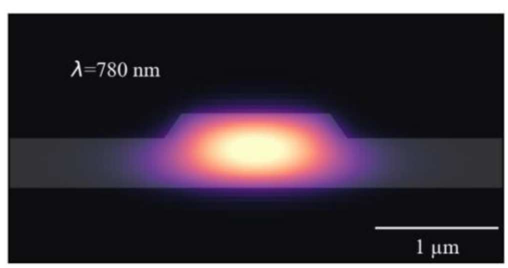


Figure 2: Simulated mode profile of the fundamental and second harmonic overlaid on the PPLN rib waveguide shape.

On the 1550 nm input side, the PPLN waveguide uses a double inverse taper [8] to expand the mode to a mode-field diameter of 3.6 µm with an effective index of 1.5. On the 780nm output side, because of the higher confinement at the shorter wavelength, a conventional taper is used to slightly expand the mode to a diameter of 1.3 µm by 0.6 µm. After the packaging, the insertion loss at 1550 nm input is 6 dB while the loss at 780 nm output is 13 dB since the output conventional taper cannot expand the mode significantly to perfectly match the mode in the TriPleX. In addition, the output taper is expected to have higher reflection losses since it has a higher index than the input inverse taper.

3. EXPERIMENTS AND RESULTS

An OFDR sensing system developed to characterize the PPLN consists of two unbalanced Mach-Zehnder interferometers (MZI): k-space interferometer and main interferometer, as shown in Figure 3(a). Both interferometers are constructed using all polarization-maintaining fibers (PMF) to prevent any detrimental polarization fading effects. The k-space interferometer with a free spectral range of 1.57 GHz serves to compensate the nonlinearity imposed onto the continuous optical frequency sweep, using Hilbert transform compensation method [4]. This approach enhances the depth resolution and accuracy of the distance measurement within the sensing system. A distributed-feedback laser diode with an inherent linewidth of 400 kHz is modulated by an injection current to continuously sweep the laser frequency. This provides a frequency sweep range of 100 GHz at 100 Hz, corresponding to a spatial resolution of 1.5 mm in air, equivalent to the spatial resolution of 1.03 mm in optical fibers with the refractive index of 1.456. The optical frequency tuning coefficients of this laser are -1.0 GHz/mA for the injection current and -11.6 GHz/°C for the laser temperature.

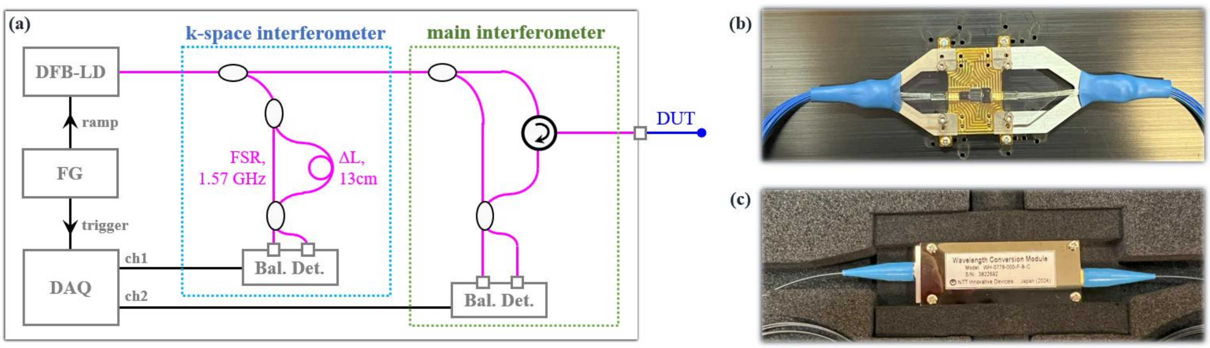


Figure 3: (a) OFDR sensing system, consisting of two unbalanced MZ interferometers. (b) LOLIPOP PPLN fabricated in the framework of the LOLIPOP project using hybrid integration between silicon nitride and lithium niobate. (c) A commercial PPLN as benchmark wavelength conversion device.

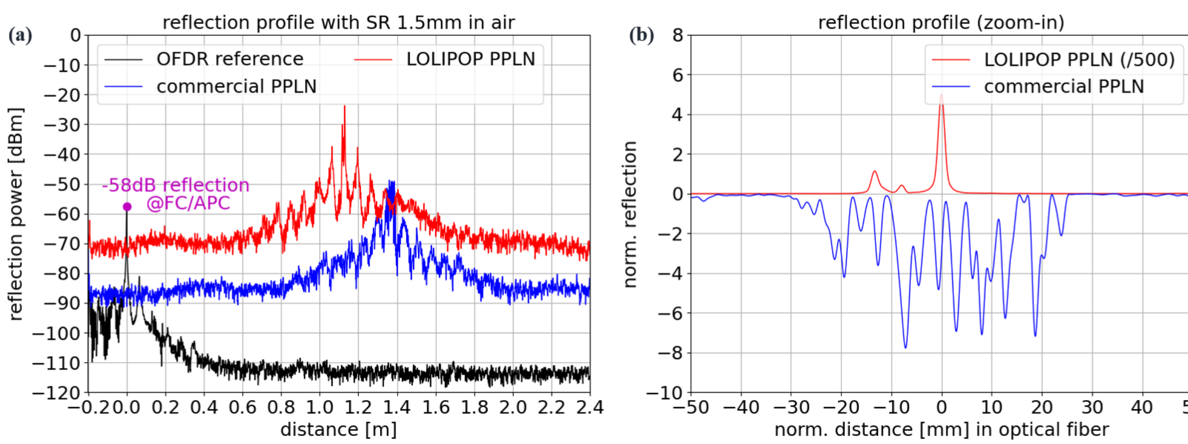


Figure 4: (a) Distributed reflection profiles, measured along the LOLIPOP and commercial PPLNs. (b) Reflection profiles zoomed-in along the section of PPLN.

The reflection profile of the OFDR is measured while the output of the senisng system with a FC/APC connector is exposed to the air, as shown by the black profile in Figure 4(a). The inevitable Fresnel reflection from the 8° angled facet is clearly observed, and its position is set to the reference sensing distance at 0 m. In addition, the reflectivity from this connector is measured to be -58 dB, which is obtained from the calibration process that will be discussed later. Prior to the investigation on the LOLIPOP PPLN (See Figure 3(b)), a commercial PPLN based on bulk lithium niobate waveguides supplied by NTT Innovative Devices Corp. (See Figure 3(c)) is tested. This device is also fabricated for second harmonic generation from 1560 nm to 780 nm. The 1560 nm port of this device is then connected to the reflectometry system. Multiple reflection peaks are observed, starting at the 1.34 m position (See Figure 4(a)), which matches well the physical length of the pigtail fiber of the device. A presumably periodic reflection profile with a periodicity of 3.28 mm is observed over 45.3 mm while the actual poling period is theoretically expected to be 20-30um. When considering the refractive index of bulk PPLN ~2.0, it demonstrates a good agreement with the actual PPLN length of 34 mm. The periodic reflection pattern will be further investigated, using a higher spatial resolution. However, notice that no visible reflections are detected from the facet between the optical fiber and the waveguide, confirming the high-quality assembly and packaging of the device.

The LOLIPOP PPLN is then connected to the sensing system for the characterization. At first glance, three significant reflections are detected, which are ~25 dB stronger than the reflection from the commercial PPLN, as shown by the red profile in Figure 4(b). Using an optical powermeter, the optical power of the reflected signal is measured to be 8 μW while the OFDR output power is 1.7 mW; hence, resulting in the reflectivity of about -23.3 dB. This value is then used to calibrate the absolute reflectivity level of the signal reflected through the LOLIPOP PPLN. As expected, the first peak at 1.12 m aligns well with the physical length of the device's pigtail. We can confidently mention that those three peaks correspond to the 3 facets of OFA1-SSC1, SSC1-PPLN and PPLN-SSC2 (See Figure 1). An optical loss and reflection are unavoidable due to two main factors: the cross-sectional design of different platform components is optimized for a specific wavelength, and there is an imperfect matching in the mode field diameter between the components. The three peaks are distanced by ~5.4 mm and ~7.9 mm while the physical length of both SSC1 and PPLN is ~5 mm. Considering the effective refractive index of n=1.52 for SSC and n=1.92 for PPLN, the measured length is compensated to 5.2 mm and 6.0 mm for SSC and PPLN, respectively, showing a good agreement. However, notice that the specific feature of the periodic reflection profile along the PPLN structure is not visible due to the reflections from the facets, completely screening out possible reflections from the LOLIPOP PPLN. We will conduct more measurements using an OFDR with higher spatial resolution, so that the reflection profile through the LOLIPOP PPLN will not be influenced by the rising and falling tail of the three strong peaks.

4. CONCLUSIONS

In conclusion, we have successfully fabricated and characterized periodically poled lithium niobate through the hybrid integration, combining two distinct platforms: silicon nitride and lithium niobate. The reflection properties along the fabricated PPLN are precisely investigated using an OFDR sensing system with a spatial resolution of 1.02 mm. Due to the complexity of the hybrid integration process, strong reflection in the range of -20 dB is present at each hybrid coupling facet. Such reflections can be problematic for applications that require the precise detection of signals counter-propagating through the device. Nevertheless, we believe that the in-situ monitoring of the device fabrication process by the OFDR sensing system offers a promising solution, for characterizing hybrid photonic integrated devices.

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REFERENCES

[1] J. Liu, G. Huang, R.N. Wang, J. He, A.S. Raja, T. Liu, N.J. Engelsen and T.J. Kippenberg, "High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits," Nat Commun. **12**, 2236 (2021).

[2] J. Lu, J.B. Surya, X. Liu, A.W. Bruch, Z. Gong, Y. Xu and H.X. Tang, "Periodically poled thin-film lithium niobate microring resonators with a second-harmonic generation efficiency of 250,000%/W," Optica **6**, 1455-1460 (2019).

[3] M.G. Vazimali and S. Fathpour, "Applications of thin-film lithium niobate in nonlinear integrated photonics," Adv. photonics **4(3)**, 034001 (2022).

[4] T.J. Ahn, J.Y Lee, and D.Y. Kim, "Suppression of nonlinear frequency sweep in an optical frequency-domain reflectometer by use of Hilbert transformation," Appl. Opt. **44**, 7630-7634 (2005).

[5] C.G.H. Roeloffzen, M. Hoekman, E.J. Klein, L.S. Wevers, R.B. Timens and D. Marchenko, "Low-Loss Si3N4 TriPleX Optical Waveguides: Technology and Applications Overview," IEEE J. Sel. Topics in Quantum Electron. **24**, 1–21 (2018).

[6] J. Leo, M. Hayati, F. Agri, Z. Haddad, G. Choong, Y. Petremand, I. Prieto, O. Dubochet, M. Despont, H. Sattari, and A. Ghadimi, "Wafer-scale fabrication of low-loss waveguides in lithium niobate on insulator (LNOI) integrated photonics platform," in European Conference on Optical Communication (ECOC) 2022, paper Mo3F.4.

[7] C. Franken, S. Ghosh, C. Rodrigues, C. Xin, K. Powell, J. Yang, S. Lu, N. Sinclair, K. Boller, and M. Lončar, "Sidewall poled lithium niobate ridge waveguides for efficient UV generation," in CLEO 2024, paper SM4N.1.

[8] L. He, M. Zhang, A. Shams-Ansari, R. Zhu, C. Wang, and L. Marko, "Low-loss fiber-to-chip interface for lithium niobate photonic integrated circuits," Opt. Lett. **44**, 2314-2317 (2019).