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Executive Summary of the Thesis

Femtosecond-laser-written wavelength division multiplexer for quantum photonics applications

Laurea Magistrale in Physics Engineering - Ingegneria Fisica

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1. Introduction

1.1. Background

Quantum technologies have the potential to revolutionize the way we process information. This new approach could lead to dramatically increased performance in fields such as computing, simulation and communication. Although the theories behind these technologies began to develop in the last decades of the 20^{th} century, the development of physical platforms capable of implementing quantum algorithms is still in its embryonic stage. Although quantum supremacy has already been achieved [2], further efforts are needed to implement a universal quantum computer. To realize a quantum computer, it is necessary to rely on a platform that is scalable, engineerable and reliable. To date, the most promising technologies use superconducting circuits, trapped atoms or ions, or photons. The latter have the particularity of low decoherence and weak interaction with the environment, keeping the information preserved for long-haul communication. These characteristics make photons a promising choice as quantum information carriers. However, the characteristic of being weakly interacting is also one of the main drawbacks, since the implementation of two-qubit quantum logic gates, fundamental for the realization of a universal quantum computer, requires photon-photon interaction. Nevertheless, in 2001, Knill, Laflamme and Milburn showed that it is possible to achieve scalable quantum computing only by using single photon sources, detectors, and linear optical circuits [3]. This discovery has greatly encouraged the use of photons as quantum information carriers. In this framework, photons have recently joined the "race to quantum computing" by demonstrating a quantum advantage on a classically intractable problem, namely boson-sampling.

Boson sampling is a quantum computational model that that exploits the interference of noninteracting bosons to solve a classically intractable problem [1]. This task belongs to a $\#P$-complete class of computational complexity and so it is not solvable in polynomial time. With up-to-date and optimized algorithm classical computers can be outperformed in a boson sampling experiment processing 50 or more photons. Recently, a task-driven photonic quantum computer [6] broke all previous records for quantum advantage, processing up to 113 photons and achieving a space-state dimension of

10^{43}. However, to scale up the complexity and go beyond a task-driven approach, it is necessary to circumvent the scalability, size (Jiuzhang is 3 square meters [6]) and interferometric stability issues of bulk-optics. In this framework, photonic integrated circuits (PICs) represent a viable solution, promising to integrate several components and functionalities on chip. Despite PICs represent a well-know and developed technology for classical telecommunication, the adoption of PICs in quantum computing is quite recent and further development should be addressed to satisfy the strict requirements set by quantum applications. When we refer to an integrated photonic quantum computer, we are speaking of a device which encompasses not only the processor unit, but also single photons detectors and sources. It follows that the development of an integrated source capable of generating complex input states is a fundamental key to the implementation of complex photonic circuits.
In general, integrated sources are divided into probabilistic and deterministic sources. Deterministic sources are based on the fluorescence of single quantum emitters and include quantum dots or colour centres. Probabilistic sources are based on spontaneous processes in nonlinear medium, such as spontaneous parametric down conversion (SDPC) and spontaneous four wave mixing (SFWM). When an intense pump laser interacts with a $\chi^{(2)}$ (or $\chi^{(3)}$) material, one (or two) photons of angular frequency ω_p are annihilated and a pair of daughter photons is generated. The peculiarity of emitting a pair of photons allows to know where and when a photon has been generated (heralded photons) thanks to the detection of the other (heralding photons). So far, due to the tremendous advances in engineering of material dispersion for high-purity generation, the room temperature operation and the ease of integration in various materials and configurations, photon pair sources based on nonlinear processes still represent the most adopted solution for the generation of high-quality quantum information carriers.

1.2. Motivation

As stated above, miniaturization, scalability and stability are the key requirements to build complex circuits and thus achieve computational complexities far beyond classical computation. Integrated photonic devices may be the solution to these problems. However, it is difficult to meet all the requirements (efficient sources, high-performance processing units, and efficient detectors) on a monolithic platform and therefore a hybrid approach could represent the fastest way to achieve quantum advantage on chip. In this scenario, Femtosecond Laser Micromachining (FLM) represents a promising fabrication technique due to its capability both to process different materials and to produce optical interconnects with high coupling efficiency. In the general framework of the project, the aim is to create a standalone heralded integrated source. This device should be capable of generating pairs of pure single photons simultaneously, filtering the pump photons from the daughter photons and splitting the heralding photon from the heralded ones, all on a chip. Finally, this source should prepare an input state with a consistent number of indistinguishable photons for the implementation of the boson sampling experiment. In this thesis project, we propose, fabricate, and characterize an on-chip wavelength division multiplexer with low losses and high coupling efficiency with standard single mode fibers for splitting the heralded from the heralding photons.

2. Materials and Methods

2.1. Fabrication of integrated photonic devices

All the devices reported in this thesis were fabricated by means of Femtosecond Laser Micromachining (FLM) in borosilicate glasses. FLM is a powerful and versatile technique that, using ultra-short laser pulses and tight focusing, is able to generate a nonlinear absorption process within a dielectric transparent material, inducing a localized and permanent modification in the substrate. The laser system is usually combined with a high-precision computer-controlled translation system, on which the sample is fixed. By moving the sample in the three dimensions relative to the focal point of the laser beam, it is possible to fabricate 3D circuits, showing a huge advantage in design flexibility over conventional planar lithographic techniques. Furthermore, being a maskless and single-step technique, FLM is particularly suitable for small-scale production and fast-prototyping. In addition, relying on the nonlinear laser-material interaction, FLM can be adapted to different transparent materials, making it a versatile technology. Indeed, several processing parameters as focusing conditions, laser repetition rate, laser wavelength, pulse energy, translation speed, can be tuned to optimize the performance of laser-written PICs according to the processed material. Furthermore, since the modifications induced in the material are usually comparable in terms of size and refractive index contrast to the one of single mode fibers, PICs written by FLM typically show very low coupling losses when interfaced with standard and off-the-shelf fiber-optical components.

The devices were fabricated in the laboratories at the Physics Department of Politecnico di Milano under the supervision of Dr. Roberto Osellame, head of the Fast Group and Director of Research at the Institute of Photonics and Nanotechnology (IFN - CNR). In particular, for the fabrication of the devices explained in this thesis, a commercial femtosecond laser PHAROS, by LIGHT CONVERSION, was used. This laser system features a Yb:doped crystal as nonlinear medium and emits laser pulses at a wavelength of 1030 nm. The laser can achieve an average power of 10 W. The laser can be controlled by a factory software and it is possible to easily adjust parameters such as repetition rate (from single shot to 1 MHz), pulse duration (from ps to 190 fs) and others. However, for all the fabrication performed in this thesis, we set the pulse duration to 172 fs and the repetition rate to 1 MHz. The average power of the outgoing laser beam is then controlled with a system of polarizing optics encompassing a computer-controlled half-wave plate and a polarizer. The beam is then steered using micro-metrically adjustable mirrors into the objective and focused into the substrate, which is fixed onto a three-axis stage. A sophisticated linear motion system (Aerotech ABL1500), equipped with air bearings and linear brushless electric motors for smooth and highly accurate translation (down to 100 nm), allows the movement of the substrate for a total volume of 10 cm × 15 cm × 5 cm at speed up to 100 mm/s. The stage movements are programmable via software, namely A3200 CNC, using GCode language. After fabrication, the sample undergoes annealing, which is a thermal process that is performed to relax the internal stresses formed during the fabrication process. According to literature, this process allows the fabrication of optical waveguides with state-of-the-art performance both in terms of propagation and coupling losses. The optical circuits are finally prepared for the characterization by polishing their facets to optical quality.

2.2. Characterization methods

The fabricated devices consist generally of straight waveguides and evanescently coupled waveguides. Optical characterization techniques are typically adopted to assess both their behaviour and their waveguiding properties, as insertion losses, propagation losses, and guided mode profile. All these measurements are typically performed by coupling the input ports of the devices with standard single-mode fibers and by steering the output light into a powermeter head or a high-resolution camera by means of an objective lens. Coupling and positioning of the optical elements are performed through either manual or piezoelectric micropositioners. By this procedure, it is possible to measure the insertion losses (IL), i.e. the optical power attenuation experienced by the input signal due to the insertion of the device in its path. They are measured in decibel and are expressed as follows:

$$IL_{\mathrm{dB}} = -10\ log_{10}\left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}\right), \tag{1}$$

where P_{in} and P_{out} optical powers at the device input and output, respectively. The IL are the sum of the contributions of different types of losses: Fresnel Losses, arise from the mismatch in the refractive index of waveguide material and the air, Coupling Losses, originating from the mismatch of the electric field profile of the light impinging the input facet and the mode supported by the waveguide, Propagation Losses, namely the attenuation of the light caused by propagation in the waveguide and finally Bending Losses, the losses that occur when light experiences a curved trajectory. An effective way to assess propagation losses and coupling losses is the so-called "cutback". In the cutback, the insertion losses of a sample of length L are measured. The chip is then cut in shorter length

L_2 and L_3. For each length L_i, insertion losses are measured. After at least 3 points are acquired, a linear regression is performed. The intercept represents CL, while the slope represents PL. While a practical method to measure BL is by characterizing a device encompasses straight waveguide and waveguides containing curved segments with different radii of curvature, keeping fixed the total length of the bend path. The BL can then be retrieved from the difference in IL between the curved waveguides and the straight one. The last characterization that needs to be introduced is the measurement of the extinction ratio (ER), a value that quantifies the extinction of light from one optical path to another. When dealing with a directional coupler, the extinction rate identifies the ratio between the power transmitted in the target output port with respect to the one in the other branch.

3. Optical Filter for Heralded Photon Source on Chip

3.1. Chip design

As stated in the introduction, efficient sources of quantum states of light represent a critical and essential component for the realization of a photonic quantum computer on chip. First, we briefly introduce the general scheme of the heralded source. Then, we describe in details the thesis project. The heralded integrated source will consist of four parts. The first part is used to divide the laser beam into several waveguides, equal to the number of channels that will enter the following nonlinear crystal. It is worth noting that beams in different arms should be phase locked, thus the integrated approach for splitting the pump beam. This part will be implemented by cascading N rows of 50:50 directional couplers and thus obtaining 2^N branches. Directional couplers, which will be discussed in more detail later, redistribute light by means of evanescent field coupling. The second part involves the generation of photon pairs, namely signal and idler by means of the SPDC process in a nonlinear crystal of periodically poled potassium titanyl phosphate. The last two parts consist of filtering the generated photons. In fact, firstly, the daughter photons will have to be filtered out by the pump photons, as the latter are orders of magnitude more intense and would instantly saturate the detectors. Since it is not easy to achieve filtering with high extinction levels, the implementation of this part has yet to be defined. Next, the heralding photons should be separated from the heralded ones. This thesis project will consist in the fabrication and optimization of this filter in FLM platform. In particular, this function will be performed by implementing a wavelength division multiplexer (WDM), discussed in detail below.

3.2. WDM

A wavelength division multiplexer (WDM) is a device capable of routing an optical signal composed of several wavelengths into signals composed of the individual wavelengths. In this thesis the WDM will be implemented through the engineering of a directional coupler. A directional coupler (DC), as mentioned before, is a component that redistributes optical power through evanescent field coupling. It consists of two non-interacting, parallel waveguides that approach each other via a curved section of radius of curvature r, remain close for an interaction length L at an interaction distance d and then return to the initial distance D. By changing the parameters d and L, it is possible to engineer the DC to achieve the desired power distribution at the two outputs, according to the so-called "splitting ratio". Therefore a WDM based on directional couplers divide photons with two different wavelengths (λ_1, λ_2) entering from the same input into the two different outputs of the DC. If the two waveguides are identical, namely have the same refractive index contrast, they form a synchronous directional coupler, asynchronous otherwise. In synchronous DCs, the power transfer between the two branches is complete. So considering a synchronous DC, calling reflection R (or bar) the output branch of the same waveguide where light is injected in and transmission T (or cross) the adjacent branch, we can express the normalized powers of the branches as follows:

$$\begin{cases} R(z) = \cos^2(\kappa z + \phi_0) & \text{(2a)} \\ T(z) = \sin^2(\kappa z + \phi_0), & \text{(2b)} \end{cases}$$

where z is the propagation length inside the coupling region, κ is the coupling coefficient, proportional to the modes overlap of the individual

waveguides and ϕ_0 is the initial phase. The initial phase term must be added to account for the partial coupling of the evanescent field in the curved section of the initial (final) part of the coupler, where the waveguides begin to approach (recede). Since κ and ϕ_0 are wavelength-dependent, the argument within the sinusoids changes and thus for a certain interaction length L we will have the condition $R(\lambda_1, L) = 1$ and $T(\lambda_2, L) = 1$, i.e. the WDM.
The main figures of merit of a WDM are low losses and a high extinction ratio. In the literature, we can find some examples of WDM based on directional couplers. Krapick *et al.* [4] develop a WDM fabricated by photolithography using deep UV contact printing. The WDM divided the wavelengths of 1575 nm and 803 nm with an ER of 15 dB and 20.6 dB, respectively. A good feature of this device was the low propagation losses which were of 0.07 dB/cm in average. Otherwise, concerning WDMs developed exclusively with FLM, Meany *et al.* [5] fabricated a WDM for a heralded integrated hybrid source for the 1550 and 1312 nm wavelengths, achieving overall losses of 3 dB and an ER of 10 dB for both wavelengths.

4. WDM Fabrication and Optimization in EAGLE XG

The following WDMs were fabricated by exploiting femtosecond laser writing technique on a substrate of Corning EAGLE XG borosilicate glass. Since our source will emit photons at telecom wavelengths, we decide to develop the WDM for a photon pair at 1310 nm (heralding) and 1550 nm (heralded). Thanks to previous work and competence in the group, it was possible to start the activity having an optical waveguide, already optimized for working at both the selected wavelengths. Optimized waveguides feature propagation losses around 0.2 dB/cm and a single Gaussian mode of almost circular profile of 6.5 μm and 8 μm $1/e^2$ diameter for 1310 nm and 1550 nm respectively. The directional couplers are designed with a distance between the non-interacting waveguides of 127 μm because it matches the standard outputs of the fiber arrays and using a curvature radius of 30 mm since is the optimal trade off for obtaining waveguides with low bending losses while maintaining a compact device. So at this point we proceed with engineering the d and L parameters to obtain the WDM. The first fabrication was performed inscribing a set of couplers with L equal to 0 and varying d from 6 to 11 μm in steps of 0.5 μm. Each coupler was characterized by measuring the reflection according to the formula $R = P_{bar}/(P_{bar} + P_{cross})$, where P_{bar} and P_{cross} are the powers measured at the bar and cross branch. The data are depicted in Figure 1.

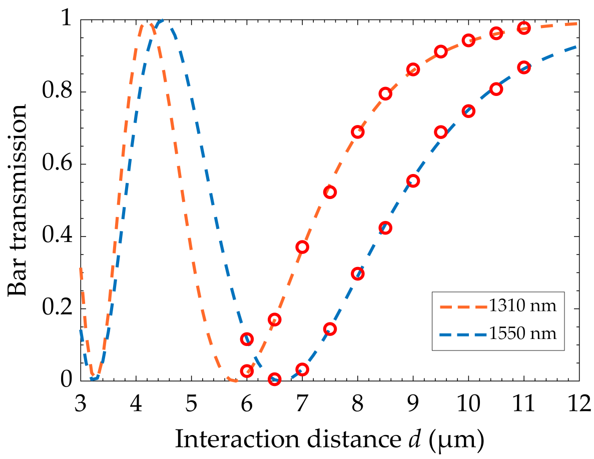

Figure 1: Experimental data of the Bar transmission in function of the interaction distance d, maintaining L fixed to 0 mm.

This first fabrication was carried out by varying d because, since κ decreases exponentially with d, accordingly with the exponential trend of the evanescent field in the region between the two waveguides, it is possible to derive the parameters a and b of the exponential trend $\kappa = a{\cdot}e^{-b \cdot d}$. This analysis was performed by means of a custom Matlab program. This program, by setting the geometrical parameters of the coupler, calculates the coupling coefficient for each segment dL of the curved section by making a guess on the parameters a and b and varying them in an iterative way until it finds the values that best fit the data obtained experimentally. Once the parameters a and b for both wavelengths have been obtained, it is possible to perform simulations of the trends of the reflections of both wavelengths for each d and thus find the L corresponding to the point of maximum division of the two wavelengths, i.e. the WDM. To verify the robustness of the simulation we fabricated on the same sample others groups of couplers keeping d fixed and varying L from 0 to 2 mm, every

0.2 mm, resulting in deviations from the fitted trend with an error between the κ of 3.16% and 1.55% for 1550 and 1310 nm respectively. The simulations showed a promising point adopting $d = 8\,\mu$m at $L = 2$ mm. So we fabricated DCs with d around the optimal d with steps of 0.1 μm and around the simulated L in steps of 0.05 mm. Finally, we measured the ER for the WDM with $d = 8\,\mu$m at $L = 2$ mm and $d = 8\,\mu$m at $L = 2.025$ mm. The former showed an ER of 22.4 dB and 24.1 dB for 1310 nm and 1550 nm, respectively, while the latter showed an ER of 25.2 dB at 1310 nm and 19.9 dB dB at 1550 nm.

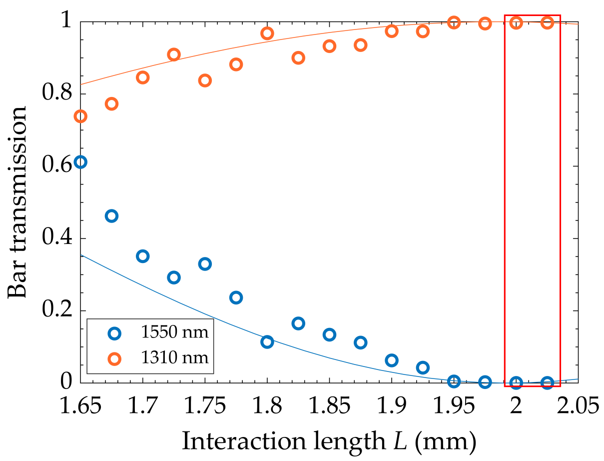

Figure 2: Bar transmission measurements for wavelengths of 1310 and 1550 nm for coupler with $d = 8\,\mu$m and L variable from 1.65 to 2.025 mm with a step of 0.025 mm. The solid lines represent the simulations. The values of ER presented are those of the two couplers shown inside the red rectangle.

4.1. WDM for photon pair in the S- and L-band

Simulations on the source (performed by a colleague and not part of this thesis work) revealed that photon pairs emitted in the S- and L-bands have higher purity than photon pairs in the O- and C-bands (i.e. the wavelengths of the WDM fabricated before). For this reason, we examined the feasibility of fabricating a WDM for the 1510 and 1588 nm wavelengths. As the wavelengths are closer together, a larger L is needed to divide them. This means that possible errors in the simulations or fluctuations in the fabrication process are carried along the entire L, making more difficult to realize WDM with high ER. In order to fabricate WDM for these wavelengths, we first derived the trend of the coupling coefficient as a function of wavelength. To do so, we fabricated the set of couplers at $L = 0$ by varying d in order to derive the parameters a and b for five different wavelengths. Using these data, it was possible to verify the linear trend of κ as a function of λ. Subsequently, by performing WDM simulations for the wavelengths of 1510 and 1588 nm according to the method explained in the previous section, WDM were fabricated. The interaction length for this wavelength pair is, as expected, much greater than for the previous O- and C-band pair, resulting around 1 cm. Consequently, we obtained ER of 17.2 dB and 15.9 dB for 1510 and 1588 nm respectively for a coupler at $d = 8.25\,\mu$m and $L = 9.82$ mm. These values, as expected, are significantly lower than the value found in the O- and C-band pair.

5. Development of Waveguides Writing in Borofloat Glass

Having low losses is a fundamental requirement in integrated photonics and even more for the success of the boson sampling experiment. For probabilistic sources, the probability of generating simultaneous n-photon complex states decreases exponentially with n and therefore losing even one photon of the complex state implies a further exponential decrease in probability. In other words, having low losses would mean greatly decreasing the time for the experiment to succeed. For this reason we tested another material on which to fabricate WDM, namely Borofloat 33. Compared to EAGLE XG, it has a different chemical composition, resulting in a lower refractive index of 1.463 compared to EAGLE XG's 1.5 (at a wavelength of 1030 nm). For this material, an optimization almost from scratch has to be performed. Optimization was conducted for wavelengths at 1550 nm, since the source generates high-purity photons for pairs around that wavelength. The first fabrications were performed by doing a wide scan of powers, number of scans and writing speed, i.e. inspecting 10 powers from 650 to 1590 mW, with four speeds from 25 to 80 mm/s and with 1, 3, 5, 7 scans. After discarding multimode waveguides and waveguides with excessive losses we fabricated straight waveguides in the optimal window of power (from 650 to 750 mW, with 25 mW step), speed (40 and 60 mm/s) and number of scans (3, 5, 7). This fabrication was performed on a 10 cm sample in order to successively perform a cutback, method explained in section 2.2. The cutback results are shown in Figure 3. It is possible to notice that all waveguides present very low PL, around 0.03 dB/cm. These values are almost an order of magnitude lower than the competitor EAGLE XG and are among the lowest values found in literature for femtosecond laser written devices. However the CL are comparable if not higher than EAGLE XG values, due to a mode profile $1/e^2$ diameter of about $12.5\,\mu m$.

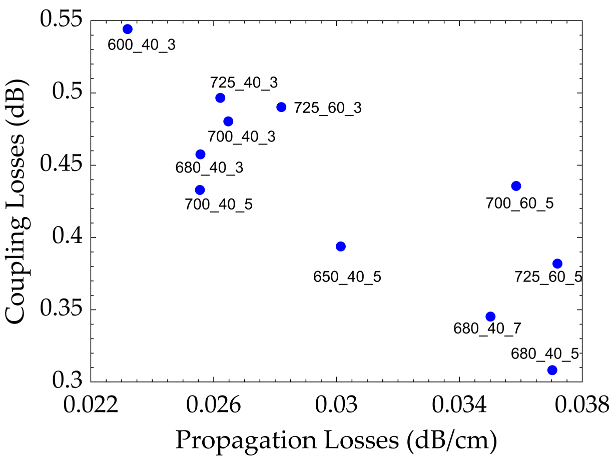

Figure 3: Coupling losses and propagation losses derived after a cutback. The nomenclature stands for power(mW)_velocity(mm/s)_scans.

We then continued by examining the BL for three best waveguides in terms of PL, CL and mode profile. We have used curvature radii of 60, 40, 30, 20, 15 mm. Using this approach, only the waveguide inscribed with 700 mW power at 40 mm/s using 5 scans was able to obtain acceptable values, showing IL below 2 dB for 40 and 60 mm beams in a 10 cm device and BL values of 0.06 and 0.1 dB/cm for 60 and 40 mm respectively. The other waveguides showed much higher loss values. Such high BL values could be related to the large mode profiles that these waveguides have, since the bigger the mode, the less confined light is in the waveguide, leading to higher radiative losses in the curved sections. Finally, we verified the coupling between waveguides. For this reason we fabricated a coupler set with variable d and $L = 0$ in order to verify the behaviour of κ in function of d and utilizing the same fabrication we derive the wavelength dependence of κ for S- and L-band wavelengths, as explained in section 3. On the same sample we fabricated sets of couplers at fixed d varying L in order to verify the robustness of the simulations, resulting in an overestimation of κ of about 2.81% and 5.96% for couplers with $d = 6.5\,\mu$m and $d = 9\,\mu$m. At this point, following the procedure explained in section 3 we fabricated a WDM for pairs of photons 1510/1588 nm obtaining as best result an ER of about 19 dB for both wavelengths, for a coupler with $d = 10.25\,\mu$m and $L = 9.44$ mm.

6. Conclusion

This thesis dealt with the development of wavelength division multiplexer, a device required for the implementation of an integrated heralded source. This device was fabricated using the femtosecond laser micromachining technique. The WDM was initially fabricated for the classical telecom wavelengths, i.e., for the 1550/1310 nm photon pair, obtaining very good results in terms of ER, namely, 24 dB and 22 dB for the two wavelengths. We then optimized a WDM for wavelength pairs in the S- and L-band. However, as expected, for the pair of photons at 1510/1588 nm we found worse results in terms of ER, obtaining 17 dB and 16 dB respectively. After that, in order to explore the possibility to fabricate femtosecond laser written waveguides with lower losses, the same approach was used to fabricate WDM using a new material, namely Borofloat 33. On this substrate, after a process of guide optimization, we were able to fabricate a WDM with ER values of 19 dB, for both wavelengths. In addition, Borofloat showed PL values about an order of magnitude lower than the competitor EAGLE XG, however featuring slightly higher bending losses. It is worth highlighting that the fabrication process of waveguides in Borofloat 33 showed a high sensitivity to fabrication depth and low reproducibility. Since the values of PL in this platform are extremely promising, further studies are needed to circumvent this issue.

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