Coupling NANF to Silicon Photonics circuits

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Abstract: We present the first demonstration of optical coupling between hollow core fibers and Silicon Photonics circuits. We achieved moderate excess coupling loss with respect to SMF-28 and achieved 25 Gb/s data transmission over NANF fibers.

1. Introduction

Over the last few years, disruptive insertion loss reduction of hollow core Nested Antiresonant Nodeless (NANF) fibers has been reported [1]. Insertion loss down to 0.22 dB/km brings this type of optical fibers at the same performance level of standard commercial single-mode fibers that present attenuation of about 0.18 dB/km. In NANF fibers about 99.9% of the light propagates in the air core and the rest of the power propagates through the silica cladding. This property places NANF fibers as the ultimate solution for low latency data communication with about 1.5 µs/km propagation delay saving over standard glass core fibers [2]. Other applications for hollow core fibers involve high optical power guiding and nonlinear optics [3]. CERN is the largest particle physics Laboratory in the world where physicists are studying the origin of the Universe by recreating the Big Bang conditions generating proton-proton collision in particle accelerators [4]. The largest particle accelerator currently in operation is the Large Hadron Collider (LHC) [5]. Particle detectors (called Experiments) are built around the interaction point to take high-resolution images of the particle collisions then analysed by the Physics community. The Experiment volume is a harsh environment with high radiation levels and magnetic field. Nowadays, tens of thousands of point-to-point radiation tolerant optical links, with a total data rate capacity of tens of Tb/s, are deployed between the Experiments and the first processing node in the network. Future upgrades of the LHC [6] involve higher flux and energy of the particle beam that translates into higher radiation doses accumulated by the optical components deployed on the detectors next to the particle interaction point. Most of the radiation tolerant optical links deployed in the CERN Experiments are based on multimode fibers, while future upgrades target the deployment of single-mode link technologies. Ionising radiation darkens solid core fibers, eventually inducing link loss [7] [8] [9]. Hollow core fibers are the perfect candidates for ultimate radiation hardness, thanks to the propagation in air of the fundamental mode. Photonic bandgap fibers have shown to be tolerant to high levels of ionising radiation [10]. The radiation tolerance of NANF fibers is currently under investigation at CERN, but based on their 100x lower light overlap with the glass it is predicted to be even better than for photonic bandgap fibers. The radiation resistant transceivers [11] in the CERN Experiments are based on radiation tolerant qualified discrete optoelectronics: VCSELs and PIN photodiodes. We have reached the radiation tolerance limit of these technologies and future upgrades of the LHC require components with higher radiation resistance [12]. Silicon Photonics (SiPh) leverages CMOS technology to fabricate optical circuits on Silicon chips. Preliminary results show high levels of radiation tolerance for Siph [13] [14]. Therefore, optical data links that combine Silicon Photonics transceivers with NANF fibers could lead to the ultimate radiation tolerance required in the next upgrades of the LHC Experiments if successful coupling between the two can be achieved.

2. Devices used

The fiber used for this experiment was a 5-fold symmetry NANF [15], designed and fabricated by the University of Southampton. The fibre design is similar to the 5-NANFs of [1], but with 27 µm core diameter and 420 nm mean capillary thickness. Fig. 1 (a) shows the SEM micrograph of the cross section. The fundamental mode field diameter is approximately 19 µm and the insertion loss at 1550 nm approximately 2.9 dB/km. One end of the fiber was butt coupled to a standard single-mode fibre by mounting both fibres onto V-groove quartz chips that were first aligned and then glued together using UV curing epoxy, Fig. 1 (b). The Photonic Integrated Circuit (PIC) was designed at CERN and fabricated through a multi-project wafer (MPW) using the iSiPP25G platform at Imec [16]. The optical signal propagates on-chip through single-mode Silicon waveguides with sizes of 450 nm x 220 nm, which are accessed vertically via grating couplers. The PIC integrates building blocks for optical transceivers like Silicon modulators based on p-n junction and Germanium photodiodes.

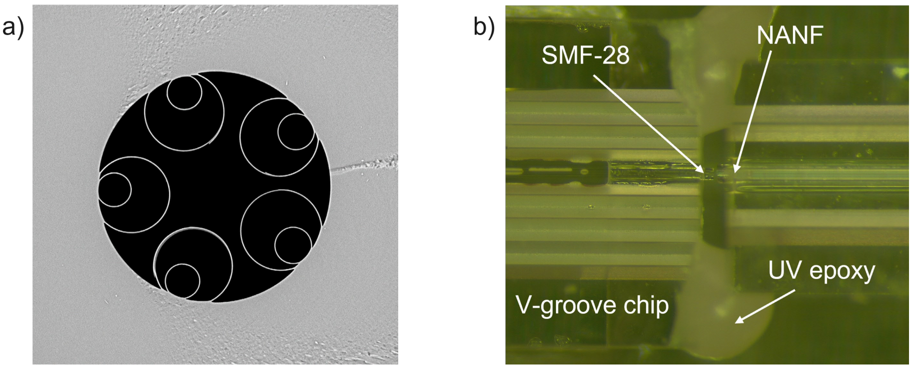

Fig. 1. (a) Scanning electron microscope (SEM) micrograph of the NANF fiber cross-section used in the experiment, (b) picture of the butt coupling permanent connection between NANF fiber and SMF-28.

3. Grating coupler efficiency

The optical coupling ports integrated on the PIC are C-band grating couplers (GC) [17]. Their spectral response peaks at 1550 nm and the passband at ± 1 dB efficiency drop is 30 nm. The insertion loss to the standard SMF-28 they are designed for is 2.5 dB, and they are designed to accept quasi-TE polarized input light. The alignment tolerance is ± 2.5 µm for 1 dB excess loss. The optimal input is a gaussian beam with about 10 µm mode field diameter (MFD) impinging onto the grating with 10° off-vertical angle. In our experiment, we mounted the cleaved NANF fiber onto a custom optical probe which enabled coupling to the PIC with the required 10° off-vertical fiber orientation, Fig. 2 (a). The probe was remotely controlled using piezoelectric actuators in the three axes XYZ. To characterise the NANF fiber to PIC alignment tolerances, we performed a two-dimensional scan in the plane of the grating with 0.5 µm step size, Fig. 2 (b). The plot in Fig. 2 (c) shows the normalised alignment tolerances between standard single-mode fiber and GC and between NANF and GC in the two axes of the PIC plane. The resulting alignment tolerances of about 1 dB excess loss for 2.5 µm fiber displacement are very close for the two types of fibers. Moreover, the coupling is reciprocal, presenting the same efficiency when coupling from the NANF into the PIC and vice versa. Due to the MFD mismatch between NANF and grating coupler (20 µm for the NANF and 10 µm for the GC) there is a penalty in the absolute coupling efficiency which we have measured to be 4 dB excess loss. This experiment is intended to be proof of concept where we used existing GCs designed to match the mode field diameter of a standard single-mode fiber. Further optimization of the coupling efficiency is possible by designing and fabricating grating couplers with input MFD matching the one of the NANF.

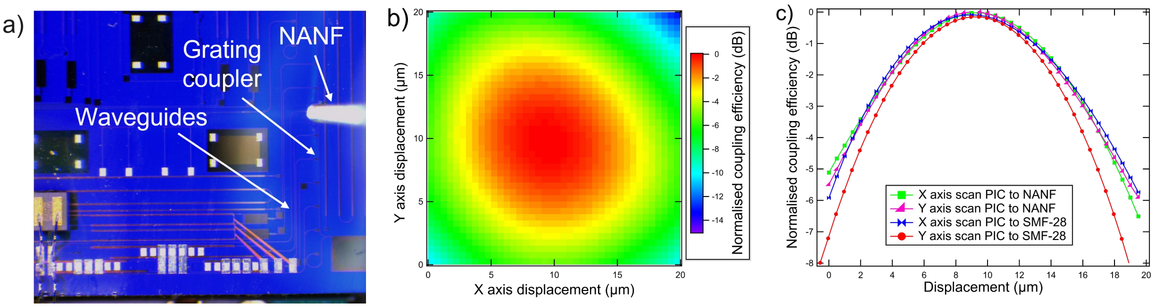

Fig. 2. (a) Picture of the optical probe setup: the NANF fiber is aligned with 10° off-vertical angle onto the planar grating coupler, (b) two-dimensional scan of the coupling efficiency between NANF and grating coupler, (c) normalised alignment tolerance between standard single-mode fiber and grating coupler and between NANF fiber and grating coupler.

4. Data Transmission Experiment

A data transmission experiment was carried out in order to show that there are no filtering effects in the coupling that degrade high-speed performance. The block diagram of the data transmission experiment is shown in Fig. 3 (a). A CW laser source is coupled into the PIC using a standard single-mode fiber and a polarization controller is used to maintain TE polarized light at the input GC. The optical signal is modulated in a 25 Gb/s Non-Return-to-Zero (NRZ) format using a Silicon Ring Modulator (RM) based on a lateral p-n junction [18]. The ring resonator presents a quality factor (Q) of about 5000 and a modulation efficiency of about 30 pm/V. Fig. 3 (b) shows the micrograph of the RM integrated on-chip. The RM was driven by a pattern generator with peak to peak out voltage of 5 V. The modulated optical signal is coupled from the PIC into the NANF fiber and propagates through about 50 m of fiber to a 28 GHz sampling oscilloscope. The optical eye diagram shown in Fig. 3 (c) is wide open showing no artifacts induced by the PIC to NANF coupling. An EDFA with 30 dB gain in combination with a 10 dB attenuator was used to amplify the signal at the output of the PIC so as to match the dynamic range of the oscilloscope input.

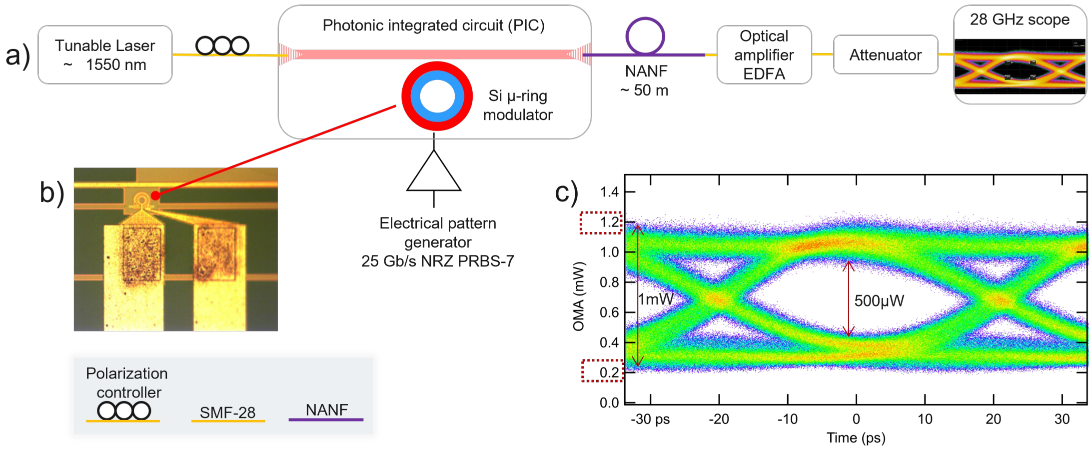

Fig. 3. (a) Block diagram of the data transmission experiment, (b) micrograph of the Silicon ring modulator, (c) optical eye diagram at 25 Gb/s of the signal after propagation through the NANF fiber.

5. Summary and Conclusions

We have demonstrated for the first time optical coupling between NANF fibers and Silicon Photonics circuits. We have measured about 4 dB excess loss compared to the use of standard single-mode fibers. Grating couplers designed to match the NANF mode field diameter could overcome this penalty. The alignment tolerance between PIC and NANF was measured to be of about ± 2.5 µm for a dB coupling drop, very similar to GCs with standard fibres. We transmitted a 25 Gb/s data-stream through 50 m of NANF, and the optical eye diagram is wide open and does not show artifacts introduced at the optical interface between PIC and NANF. We believe that this preliminary experiment paves the way for a future set of active and passive optical components with extremely high radiation tolerance to meet the needs of future upgrade of CERN Experiments.

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