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We review our recent work on silicon photonics for multicore fiber communication, including multicore fiber fan-in/fan-out, multicore fiber switches towards reconfigurable optical add/drop multiplexers. We also present multicore fiber based quantum communication using silicon devices.

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1. Introduction

Nowadays, driven by the huge capacity demand, the communication capacity over standard single mode fibers is approaching its theoretical limitation [1]. Space division multiplexing (SDM) using multicore fibers (MCFs) has shown to be a promising technology to further increase the communication capacity over a single fiber [2-4]. To achieve a real commercial success, SDM must also be compatible with optical network implementations. In particular, it should support optical routing at reconfigurable optical add/drop multiplexer (ROADM) nodes in future MCF networks, as illustrated in Fig. 1. The crucial devices are ultra-compact, high efficient MCF fan-in/fan-out (FI/FO) devices [5-8], core switches of MCFs and MCF switches [9-13].

On the other hand, in quantum communication community, similarly to classical communication, SDM can also be an efficient means to increase the information efficiency (bit/photon). So far quantum key distribution (QKD) protocols over free-space using optical angular momentum modes have been reported [14-16].

In this paper, we review our experimental results on silicon photonics for MCF communication, including crucial devices of MCF couplers, MCF switches towards MCF ROADM. In addition, we present novel QKD protocol based on MCF using silicon chips.

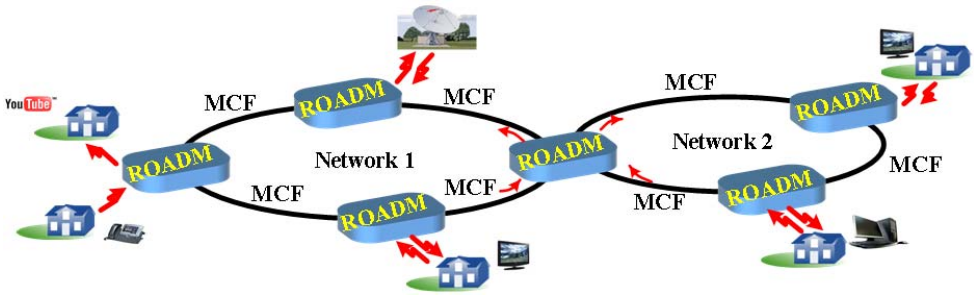

Fig. 1. A conceptual MCF network. The introduction of ROADMs enables users to drop data from and add data to the network, as well as to communicate between networks.

2. MCF FI/FO

MCF FI/FO is one of the most important devices for MCF communication. Free space based couplers [5] is an efficient solution providing high coupling efficiencies with large bandwidths and polarization independence. However, they are usually very bulky. A more compact solution by physical-contact type FI/FOs [6] has been reported. From an integration point of view, on-chip MCF FI/FOs is preferred so that many FI/FOs and other functionalities can be integrated on the same chip, making compact chip-based MCF ROADM possible. Three dimensional (3D) waveguides fabricated by ultrafast laser inscription [7] have been reported. Grating coupler based MCF FI/FO is another efficient solution [8]. As shown in Fig. 2, the layout of the output grating couplers corresponds to that of the cores of the MCF with the same pitch as the MCF. The on-chip 7-core fiber FI/FO was fabricated on the silicon-on-insulator (SOI) platform with bottom aluminum (Al) mirror that was introduced by flip-bonding method [13]. The grating couplers are fully-etched [17] so that they can be simultaneously fabricated with silicon wires in a single lithography and etching step. A highest coupling efficiency of –3.8 dB with 3 dB coupling bandwidth of 48 nm and 1.5 dB bandwidth covering the whole C band were achieved. At the same time, low coupling efficiency variation of 1.5 dB between all spatial channels with crosstalk below –32 dB were demonstrated.

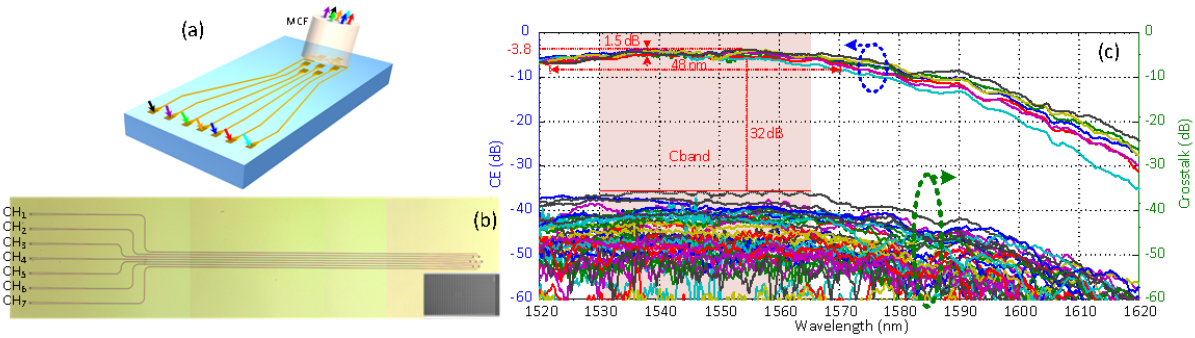

Fig. 2. (a) Schematic of the grating coupler-based MCF FI/FO. (b) Fabricated MCF FI/FI. (c) Measured coupling efficiency and crosstalk for the MCF FI/FO.

3. On-chip MCF switches towards MCF ROADM

Core switches and MCF switches are basic functionalities for MCF ROADM module. A ROADM for MCFs communication systems has been proposed using an array of wavelength-selective switches (WSSs) [9]. Micro Electro Mechanical Systems (MEMS) mirrors or on Liquid Crystal on Silicon (LCOS) pixel arrays have also been reported for MCF switching [9, 10]. All-optical nonlinear switching in MCFs has reported using high-power ultrashort laser pulses [11]. These solutions tend to have large insertion loss. Flexural acoustic waves have been used for switching in MCFs with low insertion loss [12]. Thanks to the grating coupler array based MCF FI/FO, we achieve core switching of MCFs on an SOI platform. The topological scheme is shown in Fig. 3(a), which consists of MCF couplers and 7×7 switching matrix [13]. A seven-core fiber is coupled to the input MCF coupler. After switching, the seven spatial channels are coupled to the output MCF through a second MCF coupler. In this scheme, any core of the input MCF can be reconfigurably routed to any core of the output MCF fiber. As shown in Fig. 3(a), by configuring the corresponding MZIs, the bar (solid line) switching configuration for the seven spatial channels (corresponding to different color) can be reconfigured to the cross (dash line) configuration. Fig. 3(b) shows the fabricated silicon chip, where the 7×7 switch consists of 57 Mach-Zehnder interferometers (MZIs), each incorporating a heater in one arm. Fig. 3(c) shows the transmission and corresponding crosstalk for bar configuration (core 1 input for core 1 at the output, core 2 to core 2, etc.). High transmission covering the whole C-band is obtained for all the switching paths with crosstalk lower than -30 dB. A lowest insertion loss of 4.5 dB with channel dependent loss lower than 2.5 dB is achieved. By applying proper voltages to the corresponding heaters in the 7×7 switching matrix, the silicon PIC is tuned to cross switching configuration (core 1 input for core 7 at the output, core 2 to core 6, etc.). High transmission is still obtained for all switching paths with lowest insertion loss of 5.5 dB and 2.2 dB channel dependent loss. Low crosstalk (lower than -35 dB) is obtained for the whole C-band.

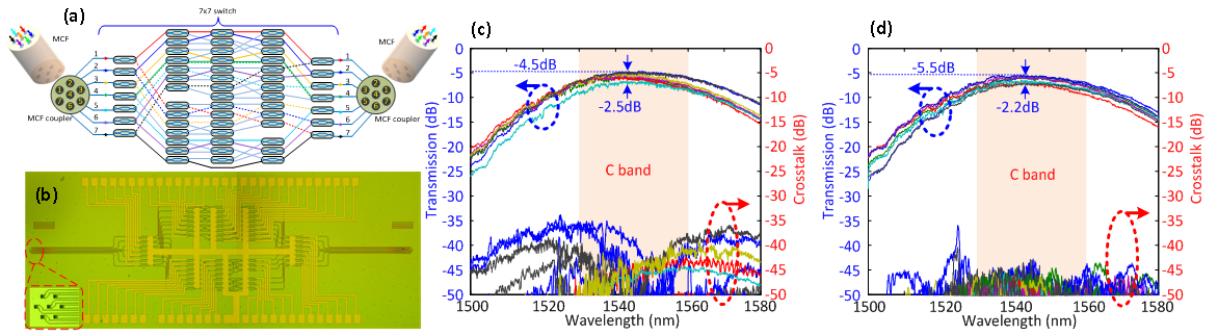

Fig. 3. (a) Topological scheme of the silicon PIC for core switch of MCFs. (b) Fabricated device. The inset shows the grating coupler array based MCF FI/FO. Measured transmission and corresponding crosstalk for (c) bar and (d) cross switching configurations.

4. MCF based QKD

Recently, the quantum community has put tremendous effort on increasing information efficiency for QKD. Usually the traditional QKD schemes are binary system, where the information efficiency is intrinsically limited to 1 bit/photon. SDM is an efficient means to increase the information efficiency. OAM modes are used to realize high-dimensional QKD protocols over free-space link [13-15]. MCF can also been utilized for QKD application. One advantage of MCFs is the crosstalk between each cores is very small, making superposition of quantum states in different cores of MCF possible. Fig. 4 shows the experimental setup of using MCF for 2 independent-BB84

protocol. Instead of using polarization domain to encode the information in traditional BB84 protocol, we use spatial (core) dimension in MCF to create two independent mutually unbiased basis, i.e. A/B base {|A⟩,|B⟩;|A⟩+|B⟩,|A⟩-|B⟩} and C/D base {|C⟩,|D⟩;|C⟩+|D⟩,|C⟩-|D⟩}. Here, |A⟩, |B⟩, |C⟩ and |D⟩ are the quantum states related to the four individual cores. Each base implements an independent BB84 protocol. Tomography measurement is carried out under the condition of weak coherent pulses (μ<0.2) of the four basis, which are also shown in Fig. 4. Good agreement between theoretical and experimental result is achieved, indicating that the two independent bases are well prepared.

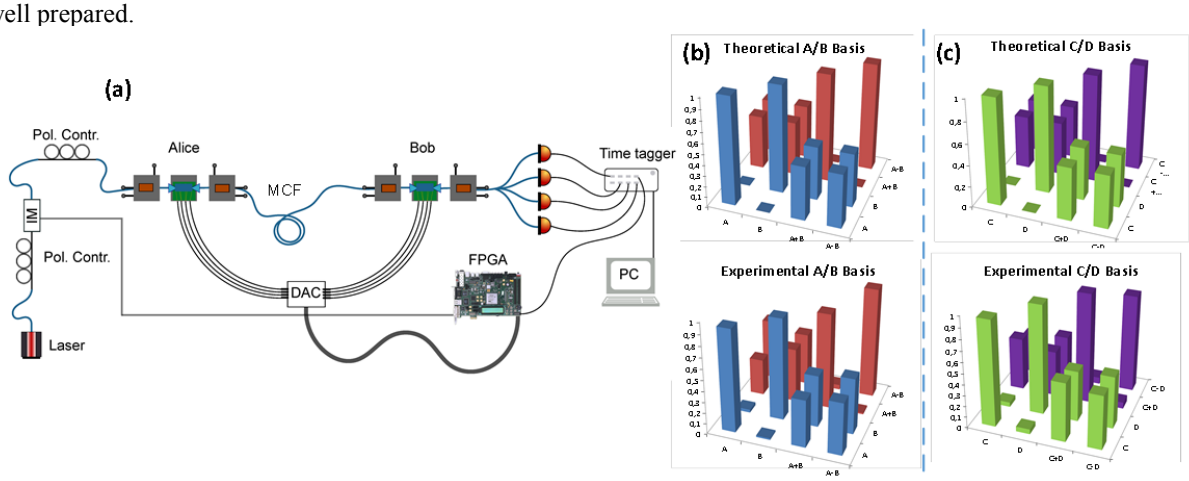

Fig. 4. (a) Experimental setup of 2 independent BB84 protocol using MCF. Theoretical analysis of quantum tomography and measured results of (b) A/B and (c) C/D base.

5. Conclusion

We have investigated silicon integrated devices for MCF communication, including high-efficiency MCF FI/FO based on grating coupler array, core switches of MCFs. We also present a novel MCF based QKD protocol using silicon photonic integrated circuits.

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