METHODS OF COUPLING HOLLOW-CORE FIBER WITH INTEGRATED PHOTONICS FOR OPTICAL NETWORKS

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Background and Introduction

With the exponential growth data exchanged over networks to support high-speed data and video services, mobile applications and cloud services, future wired access technologies will require significant technological advancements in the field of optics and photonics. Optical communication technologies have already revolutionized the field, allowing for modern high-bandwidth transmission through optical fibers. As optical access technologies evolve towards 100 Gb/s and higher data rate, transmission latency has become increasingly important, especially for time-sensitive applications such as 5G x-haul mobile networks, high performance computing, high frequency trading, etc. [1].

Many efforts have been made to reduce the latency of the networks, such as optimizing digital signal processing (DSP) in transceivers, utilizing direct-detection systems, or improving network protocol latency, etc. However, for fiber optic networks lightwave propagation speed in fiber medium is the fundamental limitation to improve the network latency. Hollow-core fibers (HCFs), using photonic bandgap to guide light within a hollow region, feature a very low overlap of the optical mode field with solid structures and allow the light propagates mostly in air [1, 2]. As a result, HCFs are considered one of the most promising solutions for low latency optical communication. Compared with traditional fused silica fiber, HCF provides a 1.54 µs/km (31%) latency reduction at 1550 nm, which offers significant advantages over exiting optical fiber technologies [1]. To make the HCFs practical in the existing networks, the HCFs need to couple with other optical components, especially integrated optical transmitters, and receivers.

In the last decades, great progresses have been made to the integration of optical components on a single chip, also known as photonic integration circuit (PIC). However, optical coupling between PIC chip and optical fiber components is still relatively challenging, due to the large size and optical mode mismatch between the optical fibers and the integrated optical waveguides. Coupling light from HCF, a special designed optical fiber with large mode area, into the integrated waveguides on PICs can be more challenging. In this invention, we proposed multiple spot size converter (SSC) designs targeting low-loss optical coupling between HCFs and PIC waveguides, including both edge and vertical coupling configurations.

Edge coupling designs

In this edge coupling SSC design configuration, the light is coupled in/out from the optical waveguide to the HCF on the lateral sides and propagating in the same plane. The first design is based on inverse taper waveguide edge coupler SSC, as shown in Figure 1. The edge coupler is fabricated on the integrated PIC platform through standard semiconductor fabrication process.

This coupler consists of two parts: an inverse taper waveguide, and a large core waveguide which is partially overlap with the inverse taper.

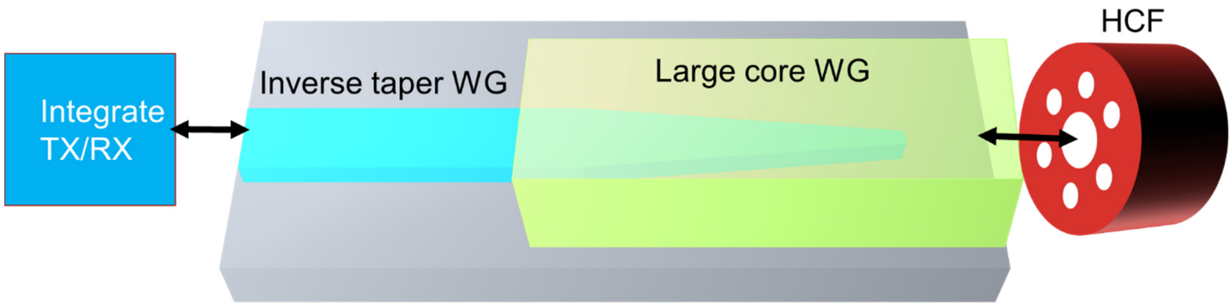

Figure 1. Edge coupling design based on inverse taper and direct coupling with HCF.

The inverse taper waveguide section is fabricated on the same device layer as the rest of the integrated optical transmitter (TX) or receiver (RX), the wider side of the inverse taper shares same dimensions with the standard waveguide of the photonics TX/RX. As the waveguide width is gradually reduced along the inverse taper, the waveguide dimensions decrease, the guided mode in the waveguide becomes less confined, this allows the optical mode gradually transferred from the inverse taper waveguide to the large core waveguide section and vise versa. Depends on the material and fabrication process, the tip width of the inverse taper is usually on the order of 100nm, where the wider side of the taper is on the order of several hundred nanometers. Also depends on specific designs, the length of the inverse taper is on the order of a few hundred micrometers. Note that both the inverse taper waveguide and the large core waveguide are covered by a cladding material that has a lower refractive index, the cladding is not shown in the Figures.

The large core waveguide section is fabricated on top of the inverse taper waveguide portion, and partially overlap with the inverse taper to allow smooth transition of the optical modes between two waveguides. This large core section features a waveguide size that is considerably larger and a lower refractive index to allow mode match between the waveguide and the HCF. Depends on the mode field diameter of the HCF, the large core waveguide has a cross-section on the order of a few micrometers in width and height. Its length is also on the order of a few hundred micrometers, to allow low loss transition of the optical mode. The HCF is butt coupled with the SSC in the horizontal direction.

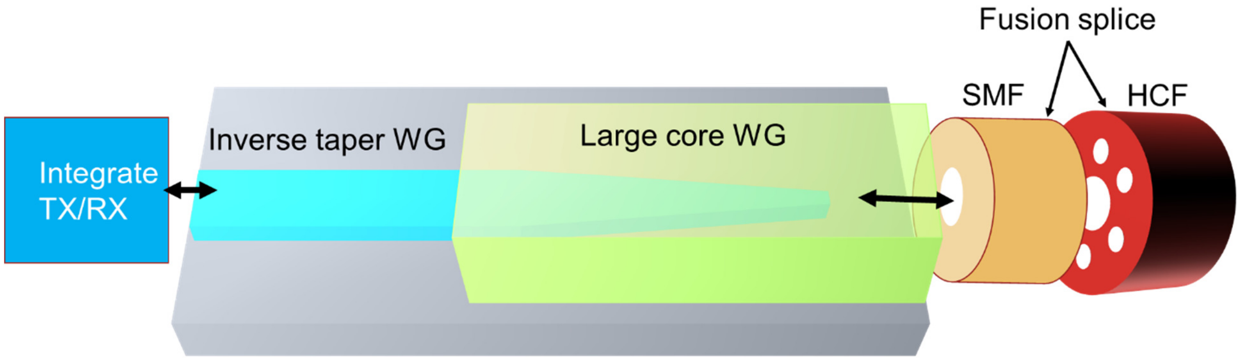

Figure 2. Edge coupling design based on inverse taper and coupling with SMF that is fusion spliced to HCF.

Another edge coupling design is shown in Figure 2. The waveguide-based SSC section is similar to the one shown in Figure 1. Between the waveguide SSC and the HCF we added a small section of regular single-mode fiber (SMF) as a transition region, as the optical mode of the HCF can sometimes be too large that even the large core waveguide could not match. In this design, coupling between the photonics chip and the regular SMF is well established and studied [3], and coupling between SMF and HCF can be accomplished with standard fusion splicing [1]. This design allows utilizing standard SSC components and fiber tools to avoid special design and fabrication requirements, can potentially reduce design and fabrication cost.

Vertical coupling designs

Another coupling configuration is based on vertical coupling through grating coupler SSC. When this technique is adopted, the optical beam is incident or exit from the top surface of the PIC chip, with a suitably designed coupling structure to modify the k-vector direction of the light, allowing coupling light into or exiting the integrated waveguide. As show in Figure 3, diffractive grating designs are widely adopted for vertical coupling. The regular waveguide in the PIC chip is tapered to a wider area with etched grating patterns which will redirect the light from the waveguide to a vertical direction and vise versa.

Design in Figure 3 utilizes a subwavelength grating design for vertical coupling, where an array of etched nano holes into the waveguide material and the fill factor of the nano holes determines the material effective refractive index. This subwavelength grating design simplifies the fabrication process by using only one etching process for both the waveguide and the grating. Other grating designs can also be adopted here, which will be discussed in Figure 5. The HCF is directly coupled with the grating coupler from the direct that is vertical to the PIC chip. Compared with edge coupling, the vertical coupling design features relatively relaxed positioning and fabrication tolerances, allows wafter scale optical testing, but also relatively sensitive to wavelength and polarization, which requires more design and optimization efforts.

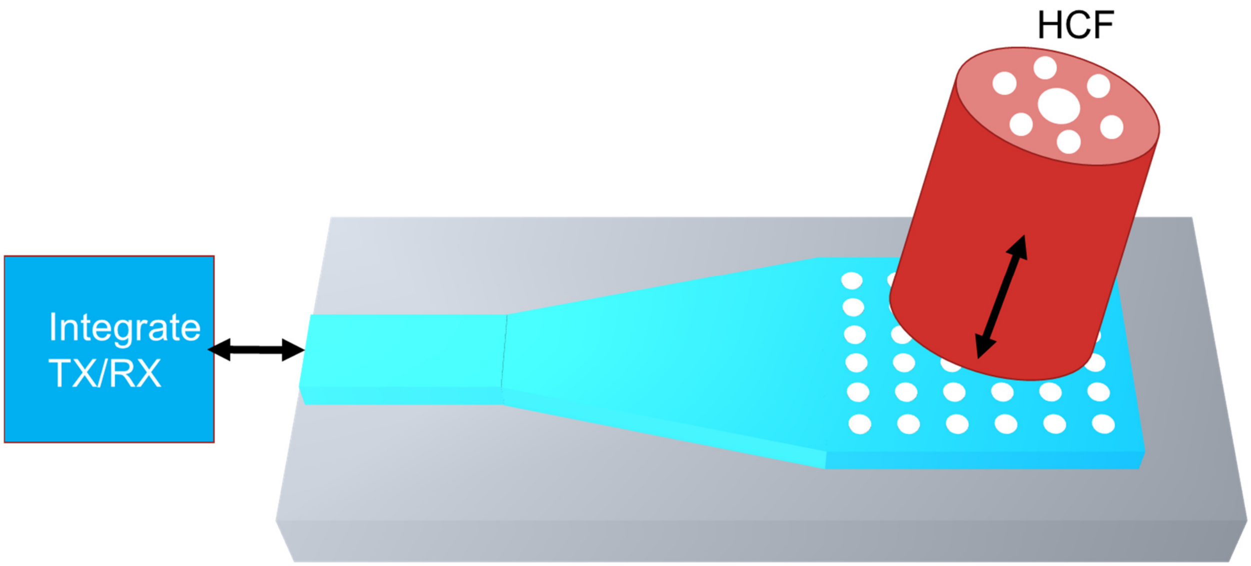

Figure 3. Vertical coupling design based on grating coupler and direct coupling with HCF.

Like the edge coupling design, the vertical coupling can also be achieved using regular SMF that is fusion spliced to the HCF. As shown in Figure 4, grating based SSC section is like the one shown in Figure 3. Instead of directly coupled with the HCF, this grating SSC is optimized for coupling with standard SMF. Between the grating SSC and the HCF a small section of regular SMF is added as a transition region. Similar to the case shown in Figure 2, this design allows utilizing existing grating SSC components and fiber tools to avoid special design and fabrication requirements, can potentially reduce design and fabrication cost.

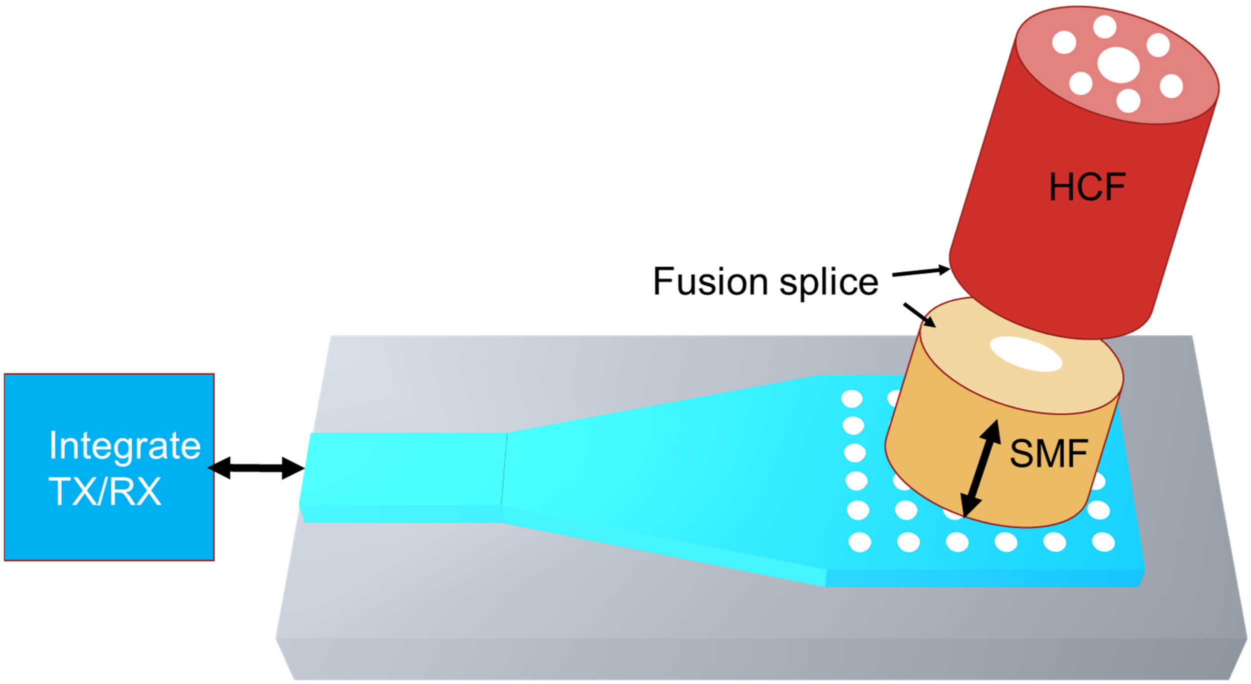

Figure 4. Vertical coupling design based on grating coupler and coupling with SMF that is fusion spliced to HCF.

For the vertical coupling design, the grating coupler can also utilize other designs such as a 1D grating, which is the most commonly adopted configuration, as shown in Figure 5. Compared with the nano-hole array grating, the simpler 1D grating is relatively easy to design and fabricate, however it usually requires a different etching depth compared with the waveguide. Depending on the HCF designs and application scenarios, the vertical SSC design can adopt different grating designs.

Figure 5. A simple 1D grating design for the vertical SSC.

In summary, we proposed two methods to enable optical coupling between integrated PIC chips and HCF. The first method uses an edge coupling design that features tapered waveguide and large core waveguide. The second method utilizes a vertical coupling design based on grating couplers. Both designs include direct coupling with HCF and coupling to HCF through a SMF transition fiber.

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