Core Selective Switch Supporting 15 Cores Per Port Using Bundled Three 5-Core Fibers

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Abstract: We prototyped a 15-core 1×8 core selective switch (CSS). The high core count CSS is achieved by bundling three 5-core fibers (5-CFs) and collimating/demultiplexing beams from the input bundled three 5-CFs using a single microlens.

1. Introduction

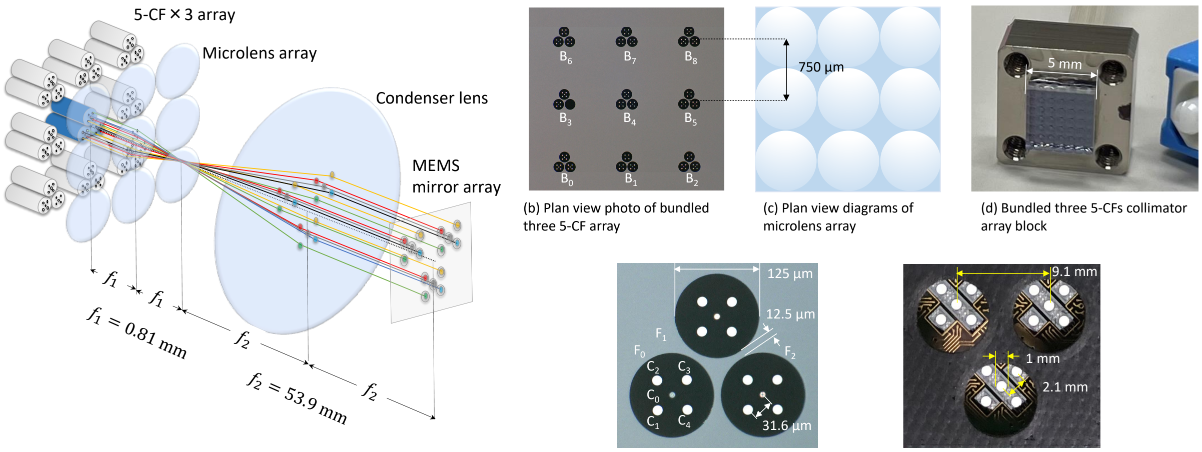
A wide variety of new fiber structures that support multiple guided spatial modes in a fiber are being developed in this decade to accommodate the ever-increasing data traffic demand [1]. Among such spatial division multiplexing (SDM) fibers, a nominally uncoupled four or five core fiber (4-CF or 5-CF) with a standard 125-µm cladding will probably be the earliest SDM fiber to market due to its higher degrees of reliability and compatibility with the current single-mode fiber (SMF) based optical transmission technology [2]. Novel optical node technologies that support SDM fibers including joint switching of a spatial superchannel [3] and a subsystem-modular wavelength cross-connect (WXC) [4] have also been investigated. However, in the optical node technologies proposed thus far, all traffic entering a node is still processed in the fine-granular spectrum domain, which may suffer from scaling and cost increase issues. The spatial channel network (SCN) architecture [5-8] was recently proposed as another approach to take full advantage of the spatial dimension. In an SCN, the current optical layer evolves into hierarchical wavelength division multiplexing (WDM) and SDM layers, and an optical node is decoupled into a spatial cross-connect (SXC) and a conventional WXC to form a hierarchical optical cross-connect [6]. Here, a spatial channel is an optical channel in the SDM layer that is constructed by connecting cores in each SDM link (a multi-core fiber (MCF) or parallel SMFs) on a route using SXCs. The SCN architecture will yield two major benefits: a reduction in the total node cost in the network and an extension to the optical reach for optical signals that spatially bypass the overlying WDM layer [5].

As a key building block for a port modular SXC, a novel spatial optical switch referred to as a core selective switch (CSS) was recently proposed [7]. A CSS is a one-input MCF and N-output MCF device where an optical signal launched into any core in the input MCF can be switched to a core that has the same core identifier of any output MCF. A 1×8 CSS supporting a 5-CF per port was prototyped using a micro-electromechanical systems (MEMS) mirror array, which exhibits low insertion loss (IL) and low polarization dependent loss (PDL) over a 1500-nm to 1630-nm wavelength range [8]. Considering that wavelength channels from 4 to 96 are used in the current WDM network, it will most likely be required that several tens or more spatial channels (cores) can be used in an SCN as well. A straightforward way to increase the core count in a CSS is to employ a high core count MCF, for example, a 19-core fiber. Another way is to use several MCFs as a bundle and collimate/demultiplex beams emitted from it all at once using a single microlens. A further increase in the number of cores is expected by using both schemes together.

In this paper, we report a 1×8 CSS prototype based on bundled three 5-CFs, which supports 15 cores per port, demonstrating the feasibility of a high core count CSS through MCF bundling.

2. Design and Implementation of CSS Prototype Based on Bundled Three 5-CFs

Figure 1 shows the implementation of the 15-core 1×8 CSS. It comprises a 3×3 bundled three 5-CF array, a 3×3 microlens array, a condenser lens, and a 3×5 MEMS mirror array each aligned in a 4-f system as shown in Fig. 1(a). The bundle of three 5-CFs in the center of the 3×3 array is used as an input port of the CSS and the others are output ports. As illustrated using ray tracing in Fig. 1(a), 15 beams emitted from the input 5-CF bundle are collimated and spatially demultiplexed by the center microlens and imaged on each corresponding mirror of the 3×5 MEMS mirror array by the condenser lens. They are steered toward their respective output ports by the MEMS mirrors, and spatially re-multiplexed into the output 5-CFs. Reflected ray traces are not shown for better visibility. Figure 1(b) shows a photo of nine 5-CF bundles arranged in a 3×3 orthogonal array at a 750-µm pitch where bundles are labeled



(a) Configuration of 1 × 8 CSS supporting bundled three 5-CFs; (b) Plan view photo of bundled three 5-CF array; (c) Plan view diagrams of microlens array; (d) Bundled three 5-CFs collimator array block; (e) Plan view photo of bundled three 5-CFs; (f) 15 MEMS mirrors

Fig. 1. Implementation of bundled three 5-CF CSS.

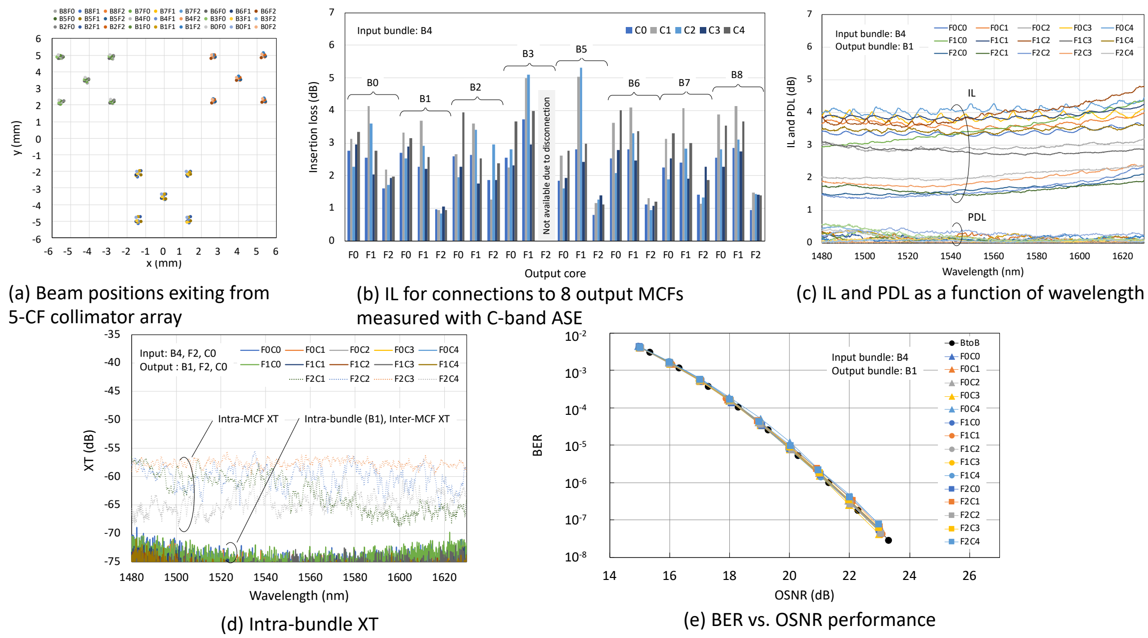
B_0 to B_8. Figure 1(e) shows an expanded image of one of the 5-CF bundles, where three 5-CFs labeled F_0 to F_3 are closely placed next to each other on the vertices of an equilateral triangle with fiber-to-fiber spacing g of 12.5 µm, while adjusting the core rotational position. The cores in each 5-CF are labeled C_0 (center core) and C_1 to C_4 (outer cores). The core spacing, c, between the center and outer cores of the 5-CF, cladding diameter d, mode field diameter, and cut-off wavelength, are 31.6 µm, 125 µm, 9 µm, and <1290 nm, respectively. The 5-CF bundle array and the 750-µm-pitch orthogonally arranged microlens array, as shown in Fig. 1(c), are assembled to form a 3×3 bundled three 5-CF collimator array as shown in Fig. 1(d). They are precisely adjusted so that each center of the three center cores of the 5-CF bundles is aligned with the optical axis of each microlens.

The 4-f system based on the microlens with focal length f_1 and the condenser lens with focal length f_2 forms a point-symmetric enlarged image of the 15 beams exiting the input 5-CF bundle on each MEMS mirror with magnification factor $M = f_2/f_1$. We first designed the 5-MEMS mirror array that has five 1-mm diameter mirrors placed at a 2.1-mm pitch in the same arrangement as the core placement in the 5-CF as shown in Fig. 1(f). The required magnification factor, M, is determined from the core and mirror pitches as $M = 2.1/0.0316 = 66.5$. The available microlens array has a 0.81 mm focal length, which requires the condenser lens focal length of 53.8 mm. Since 5-CFs in the bundle are arranged at a 137.5-µm spacing, three 5-MEMS mirror arrays are placed at 9.14 mm ($= 137.5 \times M$) spacing as shown in Fig. 1(f).

The required aperture of the microlens, D, to prevent significant beam clipping for beams emitted from the outermost cores is given by $D \geq 2(\alpha w_{col} + l)$. Here, l, w_{col}, and α are the length from the center of the 5-CF bundle to an outermost core, the spot size on the microlens given by $\sqrt{w_0^2 + (\lambda f_1/\pi w_0)^2}$ where w_0 is the beam waist of a beam at the exit facet of each core and λ is the wavelength, and clipping factor, respectively. If we need the beam clipping for beams emitted from the outermost cores to be less than 1%, α should be greater than 1.5. The l for three 5-CF bundles is given by $\sqrt{(c/\sqrt{2})^2 + \{c/\sqrt{2} + (d+g)/\sqrt{3}\}^2}$ and $2(\alpha w_{col} + l)$ is 473 µm. Since this is much less than the effective aperture of the employed microlens (750 µm), we can expect no beam clipping to occur in the three 5-CF bundled CSS prototype. If seven 5-CFs are arranged in a hexagonal closely packed structure, l is given by $\sqrt{(c/\sqrt{2})^2 + \{c/\sqrt{2} + d + g\}^2}$ and $2(\alpha w_{col} + l)$ is 587 µm. We conclude that a CSS supporting seven 5-CFs per port, which yield a high core count per port of 35, is possible using this CSS design.

3. Performance Evaluation of 15-Core 1×8 CSS Prototype

In order to know how accurately the bundled three 5-CF collimator array was fabricated, we launched a 1550-nm light wave into each core of each core of the 3×3 bundled three 5-CF array in turn and observed using a spatial beam profiler placed at the position of a MEMS mirror array. Figure 2(a) shows the overlaid beam positions. If the collimator array is fabricated ideally, beams from cores with the same fiber ID and core ID should be focused on the same position. The standard deviation of the core position relative to the design position is estimated to be 1.4 µm, indicating fairly accurate 5-CF-to-microlens positioning in the bundled three 5-CF collimator array. Figure 2(b) shows the IL of the 15 cores for the connections from B_4 to all other bundles measured using amplified spontaneous emission (ASE) in the C-band, which excludes the IL of the fan-in fan-out device used for launching the ASE. The ILs in the C-band vary from 0.8 dB to 5.3 dB. Figure 2(c) shows the typical IL and PDL characteristics (for the



(a) Beam positions exiting from 5-CF collimator array

(b) IL for connections to 8 output MCFs measured with C-band ASE

(c) IL and PDL as a function of wavelength

(d) Intra-bundle XT

(e) BER vs. OSNR performance

Fig. 2. Performance evaluation results of bundled three 5-CF CSS.

connection from B_4 to B_5) as a function of the wavelength in the wavelength range from 1480 nm to 1630 nm. The IL and PDL include those of fan-in fan-out devices used for launching light from a wavelength-tunable laser diode to each core. IL of less than 4.8 dB and a PDL of less than 0.5 dB are achieved for all cores across a very wide-wavelength range of 150 nm. Figure 2(d) shows the intra-bundle crosstalk (XT) in B_5 as a function of the wavelength. We observe that the intra-MCF XT is less than -56 dB and the inter-MCF XT is less than -69 dB. In order to confirm that there are no unknown deteriorating factors in the CSS prototype, we tested it by launching WDM signals into each core of the input bundle in sequence and routing them to the corresponding core of output bundles. The WDM signal comprises a 100-Gb/s dual-polarization quadrature phase shift keying (DP-QPSK) optical signal and dummy ASE spectrum to emulate a fully loaded spatial channel in the C-band. Figure 2(e) shows the bit error rate (BER) for the 100-Gb/s DP-QPSK signal exiting from each core in B_8 as a function of the optical signal-to-noise ratio (OSNR) of the received signal. The figure shows that traversing the CSS prototype does not incur any OSNR penalty.

4. Conclusion

We showed the feasibility of a high core count CSS using the MCF bundling scheme by demonstrating a three 5-CF bundled CSS having 15 cores per port. The CSS prototype exhibits low IL of less than 4.8 dB, and a low PDL of less than 0.5 dB over an ultrawide wavelength range of 1480 nm to 1630 nm. No OSNR penalty in the 100-Gb/s spatial channel routing was observed for all output 5-CF bundles in the CSS prototype.

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