Demonstration of Any-Core-Access Non-Directional Spatial Cross-Connects Based on Core Selective Switch with and without Core-Contention Constraint

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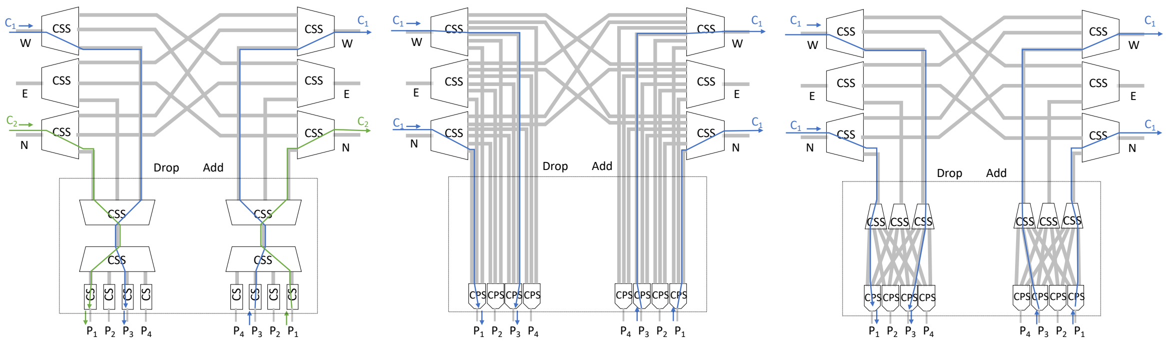
Abstract We demonstrate any-core-access (AC) and non-directional (ND) spatial cross-connects (SXCs) employing a core selective switch and core selector for spatial channel networks. In addition to AC and ND characteristics, a core-contention-less feature is achieved by introducing a newly developed core/port selector into the SXC design.

Introduction

Over the past 10 years, considerable research efforts have been focused on developing new fiber structures, *e.g.*, multicore fibers [1] (MCFs), based on spatial division multiplexing (SDM) to deal with the ever-increasing demand for transmission capacity in optical networks [2]. SDM fiber technology necessitates the deployment of high capacity optical nodes. Research efforts have also been dedicated to developing mixed-layer larger-scale wavelength division multiplexing (WDM)/SDM cross-connects based on the joint switching of spatial superchannels [3] and a subsystem-modular wavelength cross-connect (WXC) architecture [4]. However, they have disadvantages of requiring a high port count wavelength selective switch (WSS) or a large number of conventional WSSs.

Recently a spatial channel network (SCN) architecture toward the forthcoming SDM abundant era was proposed [5-10] where the current optical layer is evolved into hierarchical WDM and SDM layers and an optical node is decoupled into a spatial cross-connect (SXC) and a conventional WXC. This hierarchical architecture will allow us to accommodate a wide variety of traffic demands from the wavelength level to spatial level in a cost-effective manner. In addition, this architecture significantly extends the optical reach for spatially bypassed optical signals that pass through potentially low-loss SXCs [5]. As a growable and reliable SXC architecture, a SXC based on a 1×*k* core selective switch (CSS) was proposed [5]. Here, a CSS in an SCN provides functions equivalent to those provided by a WSS in a current WDM network.

Historically speaking, WSSs were first introduced to a simple two-degree ROADM in the broadcast and select (B&S) configuration in a WDM ring network. Then, WSSs evolved in two directions: one is increasing the node degree, *i.e.*, multi-degree ROADMs, to apply the WSS technology to mesh optical networks, and the other is increasing the connection flexibility, *i.e.*, coreless, directionless, contention-less, grid-less ROADMs, to enhance the operational automation, network resilience, and spectral efficiency. Following the history of WSS evolution, a wide variety of SXC architectures has been recently developed based on a CSS [7] and some of them were shown using a free-space optics-based CSS prototype [8]-[10]. Such architectures include a B&S reconfigurable spatial add drop multiplexer (RSADM) employing a 1×2 MCF splitter [9], a route and select (R&S) SXC with simple spatial multiplexer/demultiplexer (SMUX/SDEMUX) at its add/drop stage [8], and an R&S RSADM with a



(a) Any-core-access, non-directional SXC with core-contention (CS/CSS² type)

(b) Any-core-access, non-directional SXC without core-contention (CPS type)

(c) Any-core-access, non-directional SXC without core-contention (CPS/CSS type)

Fig. 1: Any-core-access, non-directional SXC architectures based on CSS.

core selecting device for any-core access (AC) functionality [10]. Here, the AC feature in an RSADM/SXC in an SCN corresponds to the colorless feature in a conventional ROADM/WXC in a current WDM network [7].

In this paper, we show, for the first time, AC and non-directional (ND) SXCs based on a CSS with and without the connection constraint due to core contention.

Flexible SXC architectures

Fig. 1 shows SXC architectures that provide AC and ND functionalities. They have the same line-side structure in which through ports of ingress and egress CSSs are interconnected to each other. Here, a 1×*k* CSS has a functionality to connect any core of its input MCF to the core with the same index in any of *k* output MCFs. On the other hand, the SXC architectures differ from each other in their client-side structures whose difference originates from its components and their combination.

The SXC architecture shown in Fig. 1(a) provides ND and AC features. The former is achieved by introducing a CSS pair that aggregates (distributes) light signals from (to) ingress (egress) CSSs and distributes (aggregates) them to (from) receivers (transmitters) unless core contention occurs in the MCF connecting the two CSSs. The latter is achieved by introducing a core selector (CS) [7, 10]. Here, a CS has a functionality to connect the core of an SMF to any core of an MCF. In this SXC architecture (referred to as CS/CSS^2 type), the input (output) of an unused CS on an aggregation (distribution) CSS can be connected to an unused core on an egress (ingress) MCF if and only if there is no connection from (to) another CS on the same aggregation (distribution) CSS that already uses the same core[7] (core-contention constraint).

One way to eliminate the core contention to achieve highly flexible end-to-end SCh provisioning is to introduce another additional optical device, a core/port selector (CPS), to an SXC design. Here, a CPS has a functionality to connect the core of an SMF to any core of any MCF [7]. There are two possible architectures for such SXCs relying on a CPS. One requires a high-port count ingress/egress CSS as shown in Fig. 1(b). Here each MCF port of a CPS is linked to an add/drop stage of an ingress/egress high port count CSS. This SXC architecture is referred to as the CPS type. Instead of a high-port count ingress/egress CSS, the other architecture requires aggregation (distribution) CSSs on the client side to increase the number of ports for adding/dropping and to form an *M*×*N* CSS combined with CPSs [7] as shown in Fig. 1(c), which is referred to as the CPS/CSS type.

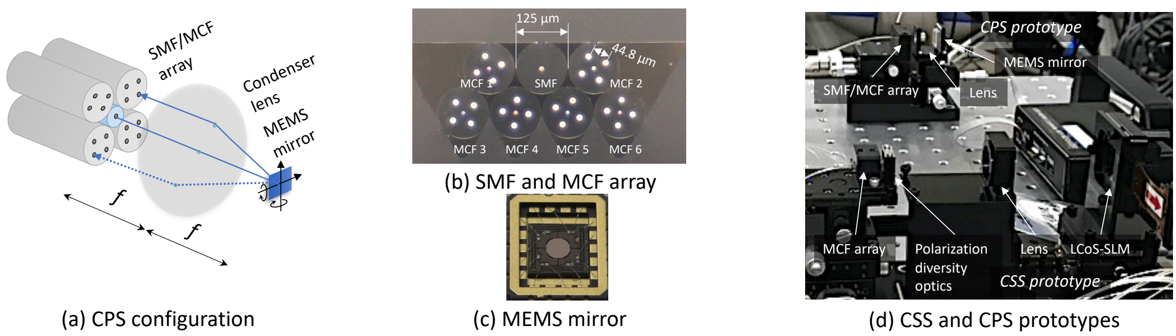
CPS prototype

A CPS can be achieved by employing simple free-space optics comprising an input SMF, output MCFs, a condenser lens, and a micro electromechanical systems (MEMS) mirror, each placed apart by the focal length of the condenser lens, *f,* as shown in Fig. 2(a). Unlike a CSS, basically no rotational alignment of the MCFs is required in the assembly process. A CS is the same as a CPS that has a single output MCF. We constructed a 1×6 CPS prototype that comprises a closely placed SMF and 5-core MCFs[11] as shown in Fig. 2(b), a condenser lens with a 10-mm focal length, and an MEMS mirror whose tilt can be controlled in two angular dimensions as shown in Fig. 2(c).

We measured the insertion loss (IL) and the polarization dependent loss (PDL) for MCFs 1-6 at 1550 nm. The IL for the outer cores (Cores 1-4) includes the excess loss of the fan-in/fan-out device [12] used for the measurement (~ 0.5 dB). Low IL less than 2.1 dB and low PDL less than 0.3 dB are achieved for all output MCFs. Inter-core crosstalk defined by the ratio of the coupled power for adjacent cores and target core is less than -35 dB for all cores in the output MCFs.

Flexible SXC demonstration

Using the CSS and CS/CPS prototypes shown in Fig. 2(d), we constructed CS/CPS^2-type and CPS-type SXCs as shown in Figs. 3 and 5, respectively. Both provide AC and ND features,



(a) CPS configuration (b) SMF and MCF array (c) MEMS mirror (d) CSS and CPS prototypes

Fig. 2: Configuration of CPS prototype.

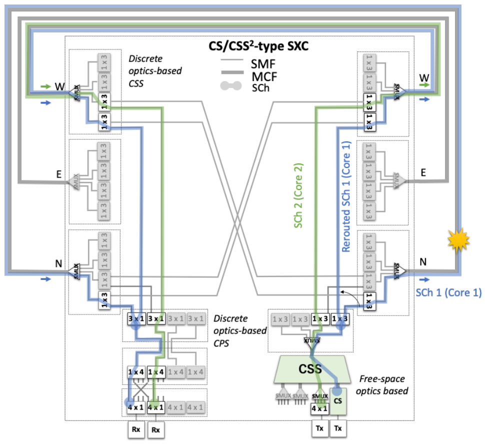


Fig. 3: Experimental configuration for CS/CSS²-type SXC.

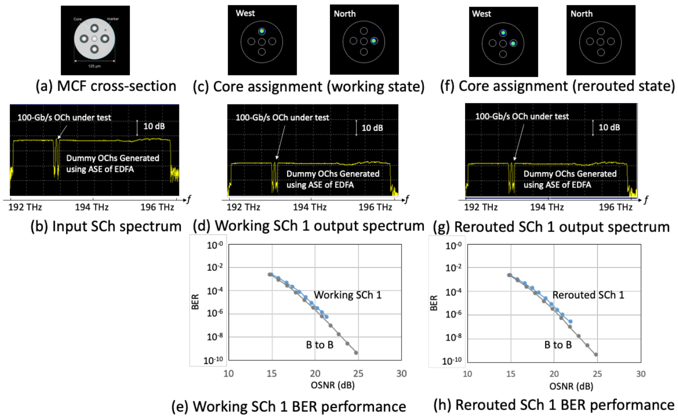


Fig. 4: Experimental results for CS/CSS²-type SXC.

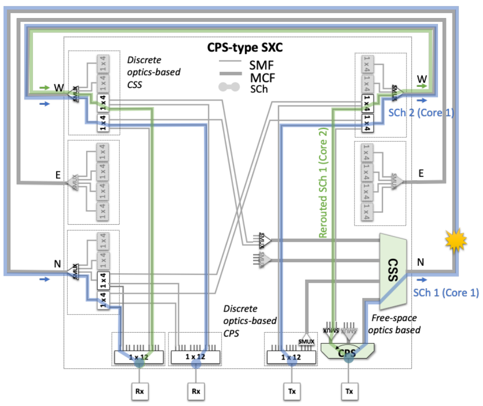


Fig. 5: Experimental configuration for CPS-type SXC.

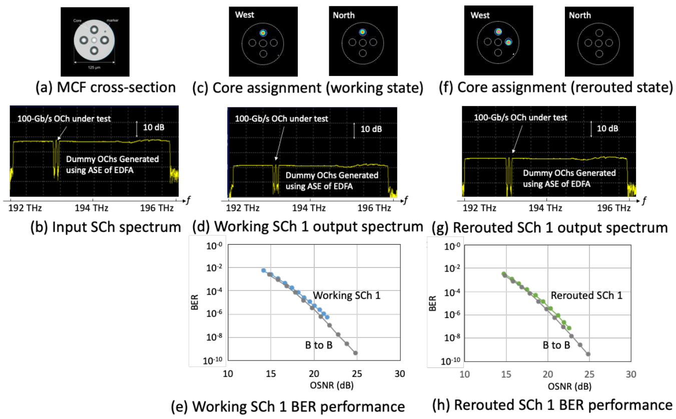


Fig. 6: Experimental results for CPS-type SXC.

but the former involves the core contention constraint, and the latter does not. Input and output MCFs for each direction on the line-side are connected to each other (loop-back configuration) to emulate a mesh SCN. Due to the limited availability of free-space optics-based CSS[8] and CS/CPS prototypes only some of the SXCs are equipped with the prototypes and other CSSs and CSs/CPSs comprising the SXC are constructed using bulk optics. We examined the feasibility of both SXC architectures over the following networking scenario: (i) establish SCh 1 heading north then SCh 2 heading west, and then (ii) in response to a fiber cut in the north, reroute SCh 1 to the west.

Fig. 4(c) shows states of the core assignment in the MCFs heading west and north in the CS/CPS²-type SXC. We can see that SCh 2 must select a core other than Core 1 (Core 2 in this example), even when Core 1 in the MCF heading west is unused, in order to avoid core contention in the add/drop stage. In the case of the CPS-type SXC with the core-contention-less feature, SCh 2 can select Core 1 regardless of the core assignment state of other MCFs as shown in Fig. 6(c). In this situation, when SCh 1 is rerouted to the west, SCh 1 must change cores to one other than Core 1 by using the CPS due to the no-core-overlap constraint in an MCF as shown in Fig. 6(f).

Quantitative characteristics of the two SXCs are evaluated by establishing and rerouting SChs whose spectrum occupies the entire C-band as shown in Figs. 4(b) and 6(b) and measuring the pre-forward-error-correction bit error rate (BER) of a 100-Gb/s optical channel (OCh) in the SCh while changing the optical signal-to-noise ratio (OSNR) of the received signals. We can see from Figs. 4(d), 4(g), 6(d), and 6(g) that the CSS and CP/CPS route the entire C-band spectrum almost uniformly as expected. A slight OSNR penalty of ~ 0.4 dB from the back-to-back performance is observed in BER vs. OSNR curves in Figs. 4(e), 4(h), 6(e), and 6(h), which are considered to be due to the imperfect anti-reflection coating of the cover glass in the MEMS mirror in the CS/CPS.

Conclusions

We showed AC and ND SXCs employing a CSS and a CS for future SCNs. In addition, a core-contention-less feature is achieved by introducing a CPS into a SXC design.

Acknowledgements

This work was supported in part by the JSPS KAKENHI (JP18H01443) and the NICT (19302/20401).

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