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A programmable optical few wavelength source for flexgrid optical networks

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ABSTRACT

Multi-wavelength (MW) sources will probably replace discrete lasers or laser arrays in next generation multi-carrier transponders (e.g., 1 Tb/s), currently called multi-flow transponders or sliceable bandwidth variable transponders (SBVTs).

We present design and experimental demonstration of a few wavelength (FW) source suitable for SBVTs in a flexgrid scenario. We refer to FW instead of MW since for an SBVT just few subcarriers are required (e.g., eight). The proposed FW source does not require optical filtering for subcarrier modulation. The design exploits frequency shifting in IQ modulators by using single side band suppressed carrier modulation. A reasonable number of lines can be provided depending on the chosen architecture, tunable in the whole C-band. The scheme is also capable of providing symmetric (equally spaced) and asymmetric subcarrier spacing arbitrarily tunable from 6.25 GHz to 37.5 GHz. The control on the number of subcarriers (increase/decrease depending on line rate) provides flexibility to the SBVT, being the spacing dependent on transmission parameters such as line rate or modulation format. Transmission performance has been tested and compared with an array of standard lasers considering a 480 Gb/s transmission for different carrier spacing. Additionally, an integrable solution based on complementary frequency shifter is also presented to improve scalability and costs. The impact on transceiver techno-economics and network performance is also discussed.

1. Introduction

The internet traffic demand is increasing dramatically with annual growth of 35% [1]. Traffic is not only increasing in terms of volume but also becoming more dynamic, requiring future networks to be more flexible (e.g., supporting multi rate). Without considering multi core/multi mode fibers, the capacity of existing networks can be increased in the near term by improving the spectral efficiency (SE) [2]. Flexible or elastic optical networks based on ITU-T flexible grid are an attractive solution enabling high SE [3–6]. At the transmission level, orthogonal frequency division multiplexing (OFDM) [7], Nyquist wavelength division multiplexing (NWDM) [8], and time frequency packing (TFP) [9] are subjects of investigations providing high SE. To cope with increased traffic dynamicity, researchers are investigating sliceable bandwidth variable transponders (SBVTs) supporting multi rate reach adaptation and the generation of several sub carriers that can be aggregated (in *super-channels*) or independently directed (i.e., supporting *slice-ability*) towards different paths and destinations [10–12].

In the example shown in the Fig. 1, the SBVT generates four subcarriers, which may support different bit rate values depending on the requests. In this case, two subcarriers at rate R_1 are routed to node *E*, a subcarrier at rate R_2 to node *B*, and a subcarrier at rate R_3 to node *D*. Subcarrier generator module provides the subcarriers. To generate several or few subcarriers, an SBVT can exploit an array of lasers (one per subcarrier) or a multi-wavelength (MW) source that can provide tens of lines. A possible alternative and effective solution is represented by the few-wavelength (FW) source, i.e., a source able to generate up to a limited number of subcarriers (e.g., from one to eight) from a single laser [12]. For this reason, we will refer to the concept of FW instead of MW. We will refer also to programmable FW source, in terms of *subcarrier spacing*, tunability, and number of generated subcarriers. As stated in [12], the control of such characteristics will be essential for SBVTs supporting multiple rates and reach adaptation (e.g., through modulation format adaptation).

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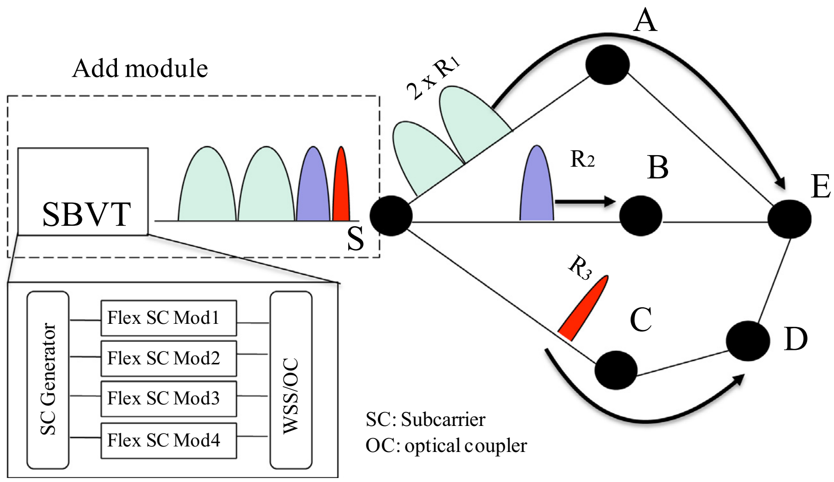

Fig. 1. SBVT generic architecture and application scenario.

MW sources or optical frequency combs have been extensively explored in the literature and several techniques have been demonstrated based on mode-locked lasers [13], semiconductor lasers [14], and electro-optic modulators [15,16]. These techniques can generate tens of comb lines with reasonable line quality i.e., narrow line-width, high extinction ratio and spectral flatness. The first type can only provide fixed free spectral range (FSR) hence not feasible for BVT (and SBVT) because subcarrier spacing cannot be varied. The modulator-based techniques can provide tunable carrier spacing but suffer from bias drift in modulators. However, drift limitation can be overcome by use of bias controllers, a standard practice in commercial applications. The possible use of MW in the flexible networks has initiated a renewed interest towards overall cost and power consumption reduction, compactness, and flexibility. Some efforts for flexible comb source have been reported recently involving use of lasers, single electro-optic modulators, and combination of modulators and different types of fibers. A flexible optical comb source based on gain switching in an externally injected DFB laser has been presented in [14]. It can generate 6 lines and subcarrier spacing can be tuned in the range 25–33 GHz. The authors in [15] demonstrated a flexible comb solution based on dual drive Mach Zehnder modulator (DD-MZM) with subcarrier spacing from 6.25 to 12.5 GHz, producing up to 9 subcarriers. In [16], the authors have demonstrated a tunable comb source which can generate 60–75 lines within 10 dB spectral bandwidth and is able to tune line spacing from 6 to 18 GHz. Keeping in view the trend of having photonic integrated solutions for transceivers and switches, it is important to choose solutions which can be integrated as well. A flexible comb with 1500 tone, 120 nm wide and line spacing tunability from 10 to 100 GHz has been presented in [17]. However, this technique involves the use of nonlinear fibers in addition to modulators, which makes it not suitable for integration. It is important to notice that all of the above-mentioned works have the limitation that subcarriers are provided from a single output. Thus, each subcarrier needs filtering to be separated and directed to the proper modulator [12] which increases the cost and complexity.

In this work, we demonstrate a filter-less, highly flexible FW source architecture, which can provide tunability of the comb, programmable and asymmetric subcarrier spacing and configurable number of lines. The comb tunability over the C-band and the configuration of asymmetric subcarrier spacing from 6.25 GHz to 37.5 GHz is experimentally demonstrated. The source can also selectively add or remove any of the lines without the need of additional filters. Finally, based on results, an integrable solution for complementary frequency shifter (CFS) has also been proposed. CFS can increase scalability by twofold without additional components and energy resources. However, similar to other MW sources discussed above, the FW source also needs amplification stage to provide the output power comparable to lasers.

The next section of the paper discusses the key practical requirements of a programmable FW source suitable for SBVTs. Section 3 explains the building blocks of flexible source design and presents the comparative analysis of different architectural and design variants. An experimental characterization of a three-line source exhibiting key flexibility features is discussed in the Section 4. Transmission performances of generated subcarriers with lasers and the proposed FW source are compared for both the symmetric and asymmetric subcarrier spacing. In the end, the impact of such sources on network performance and SBVT cost in comparison to array of lasers is argued.

2. Source features

This section discusses following specific aspects desirable in a flexible network scenario and required for an SBVT: number of comb lines and their control, tunability, spacing tunability, stability, and selectivity. A few use-case examples highlighting the need for these features are shown in Fig. 2(a–e). Fig. 2(a) shows the spectrum slices on flexgrid e.g., 12.5 GHz each and Fig. 2(b) shows a typical superchannel consisting of multiple subcarriers having the same subcarrier spacing. The symmetric and asymmetric classification is explained in the coming subsections.

2.1. Number of comb lines and their control

In practical systems, where modular solutions are preferred, a reasonable number of subcarriers will be required and techniques providing tens of lines with weak control on their number would not be feasible. Moreover, a single SBVT is expected to require the generation of a limited number of subcarriers: e.g. four to support 400 Gb/s SBVT [12] or eight for 1 Tb/s [9].

A flexible FW source should also provide the control of the number of lines, which depends on the current traffic demands. As an example, assuming 100 Gb/s subcarriers, two of them would be required to support a demand of 200 Gb/s while four need to be allocated for a 400 Gb/s. Therefore, the transceiver should be able to configure the number of subcarriers to achieve bit rate and distance adaptations as shown in Fig. 2(c). Resultantly, a FW source should provide a reasonable number of lines like 1–8.