Maximizing Spectral Utilization in WDM Systems by Microwave Domain Filtering of *Tandem* Single Sidebands

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***Abstract*—We present an optical *tandem* single-sideband receiver that enables the detection of signals having different information in the two sidebands of the same optical carrier. The technique relies on the use of a dual-electrode Mach–Zehnder modulator and achieves heterodyne detection without the use of an optical local oscillator. Sharp filtering requirements are met in the electrical domain, eliminating the need for wasteful guardbands.**

***Index Terms*—Heterodyning, optical-fiber communications, subcarrier multiplexing, wavelength division multiplexing.**

I. Introduction

There has been considerable interest in subcarrier multiplexed (SCM) systems [1] owing to applications in areas such as fiber-wireless systems [2] and multichannel video distribution [3]. However, conventional SCM systems use double-sideband modulation, reducing their spectral efficiency and increasing the dispersion penalty present in the long-distance transmission of such signals.

Approaches to improving spectral efficiency include dispersion division multiplexing [4] and spectral overlap [5], while optical single-sideband (OSSB) modulation has been proposed as a solution to both problems [2], [6]–[8]. However, wavelength division multiplexed (WDM) systems based on OSSB signals would require large guardbands between channels to accommodate the slow rolloff characteristic of optical filters [see Fig. 1(a)].

We have recently demonstrated a modification of the SSB technique, which we called *tandem* single-sideband (TSSB) modulation [9]. TSSB modulation doubles the information capacity by transmitting different information in the two sidebands of the same optical carrier. The separation between optical carriers is also doubled compared to pure SSB modulation, thus enabling easier rejection of adjacent and unwanted optical carriers by a coarse optical filter [see Fig. 1(b)]. However, TSSB signals cannot be directly detected by a photodetector since the two sidebands would interfere in the microwave domain. Using an optical filter to distinguish between the sidebands [9] is spectrally very wasteful since large guardbands would be needed between the sidebands and optical carrier.

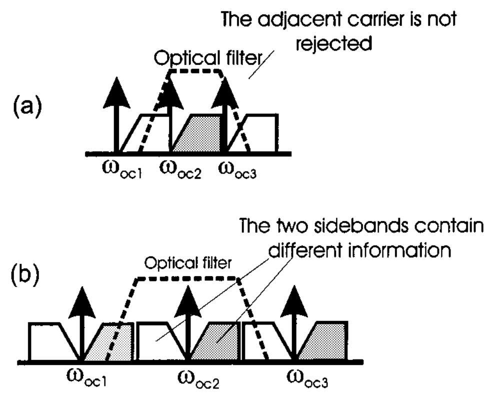

Fig. 1. (a) Pure SSB WDM systems need guardbands to prevent adjacent carriers from interfering with the desired signal. (b) TSSB signals enable carriers to be twice as far apart without wasting bandwidth. Optical channels may be separated by coarse optical filtering since the sidebands are finally separated by sharp filters in the electrical domain.

In this paper, we demonstrate a new type of TSSB receiver, which enables the reception of TSSB signals by achieving heterodyne detection without the need for an optical local oscillator (LO). The system is built using off-the-shelf components and uses sharp electrical filtering to ensure that the spectral efficiency is not limited by the slow rolloff present in optical filters.

II. Experimental Setup and Principle of Operation

A block diagram of the experimental setup is shown in Fig. 2. To demonstrate our receiver, we generated TSSB signals using the transmitter described in [9]. The light source is an external-cavity tunable laser diode (ECT–LD) tuned to f_{oc} GHz. The light from the laser is coupled into a dual-electrode Mach–Zehnder modulator (DE–MZM) through a polarization controller. An externally triggered pattern generator with 2^{23}–1 pseudorandom bit sequences (PRBSs) provides the two baseband signals. The data is used to binary phase-shift key (BPSK) modulate a sub-carrier at f_1 GHz. Even though we chose BPSK double-sideband-suppressed carrier (DSB–SC) modulation of the microwave subcarrier, more sophisticated

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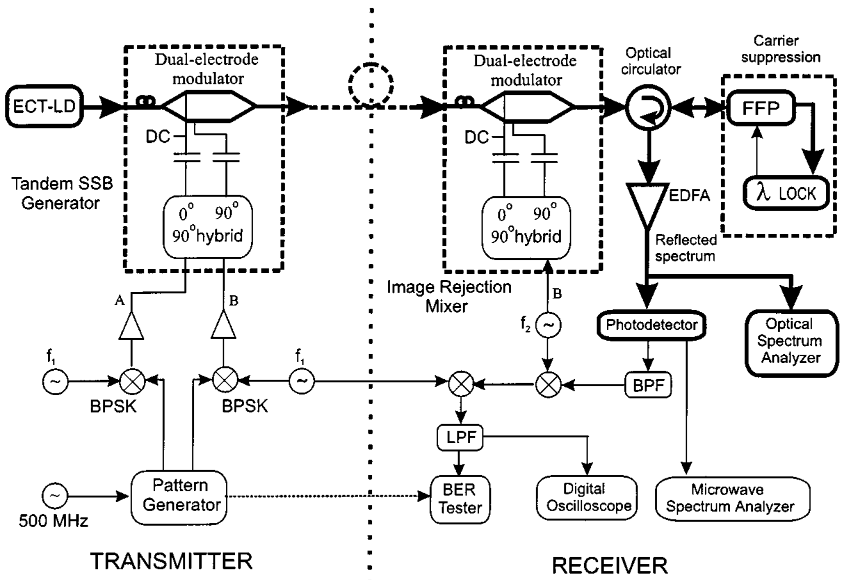

Fig. 2. Block diagram of the experimental setup.

TABLE I
HETERODYNING TERMS PRESENT AFTER PHOTODETECTOR (NO FFP)

Term #	Local Oscillator frequency	Sideband frequency	LSB/USB	IF	IF (f_1=2.5 Ghz, f_2=9.5 Ghz)
1	f_{oc}	f_{oc}-f_1	LSB	f_1	2.5
2	f_{oc}	f_{oc}+f_1	USB	f_1	2.5
3	f_{oc}	f_{oc}+f_2-f_1	LSB	f_2-f_1	7.0
4	f_{oc}	f_{oc}+f_2+f_1	USB	f_2+f_1	12.0
5	f_{oc}+f_2	f_{oc}-f_1	LSB	f_2+f_1	12.0
6	f_{oc}+f_2	f_{oc}+f_1	USB	f_2-f_1	7.0
7	f_{oc}+f_2	f_{oc}+f_2-f_1	LSB	f_1	2.5
8	f_{oc}+f_2	f_{oc}+f_2+f_1	USB	f_1	2.5

electrical modulation schemes may be chosen to further improve spectral efficiency. The two signals in arms A and B are then fed to the two inputs of a 90° hybrid coupler, the outputs of which are used to drive the quadrature biased DE–MZM through bias-T's. The signal that emerges from the DE–MZM is a TSSB signal consisting of an optical carrier at f_{oc} GHz, a lower sideband (LSB) at $(f_{oc} - f_1)$ GHz, and an upper sideband (USB) at $(f_{oc} + f_1)$ GHz [9].

At the receiver, the signal is first coupled to a quadrature biased DE–MZM. Only input B of the 90° hybrid is used and the DE–MZM acts as an image rejection mixer up-shifting the incoming optical spectrum by f_2 GHz, while suppressing the downshifted version [6], [9]. (We used only a single optical wavelength; however, in a WDM system, we would need to separate the desired channel by a coarse optical filter like the one in Fig. 1(b) prior to upshifting.)

The optical spectrum at this stage would then consist of the original spectrum centered at f_{oc} GHz (carrier at f_{oc} GHz, LSB at $(f_{oc} - f_1)$ GHz, USB at $(f_{oc} + f_1)$ GHz) and a copy of it centered at $(f_{oc} + f_2)$ GHz (carrier at $(f_{oc} + f_2)$ GHz, LSB at $(f_{oc} + f_2 - f_1)$ GHz, USB at $(f_{oc} + f_2 + f_1)$ GHz). When this signal is incident on a photodetector, the optical carrier at f_{oc} GHz and the up-shifted version of the optical carrier at $(f_{oc}+f_2)$ GHz, both serve as LOs and beat with the original, as well as with the up-shifted sidebands. Since there are two LOs and four sidebands (two original and two up-shifted), we would expect a total of $2 \times 4 = 8$ major terms from the heterodyning. The intermediate frequency (IF) at which each term would appear, would be exactly equal to the difference in frequency between the LO and the sideband signal causing it [10].

Table I shows a list of the eight heterodyne terms expected. For a TSSB signal, clearly the pairs of signals, (3) and (6), as well as (4) and (5), interfere with each other since the LSB and USB appear at the same IF. Thus, it is impossible to separate the two sidebands by this method if all eight terms are present. Eliminating terms (5) and (6) however, would enable us to recover the LSB and USB data from signals (3) and (4), respectively. Since terms (5) and (6) are obtained by the LSB and USB beating with the up-shifted carrier at $(f_{oc} + f_2)$ GHz, we may suppress them by suppressing this carrier. This does not affect signals (3) and (4) since they are obtained by the sidebands beating with the original optical carrier at f_{oc} GHz.

The up-shifted optical carrier at $(f_{oc}+f_2)$ GHz is suppressed by a fiber Fabry–Perot (FFP) of free spectral range (FSR) =

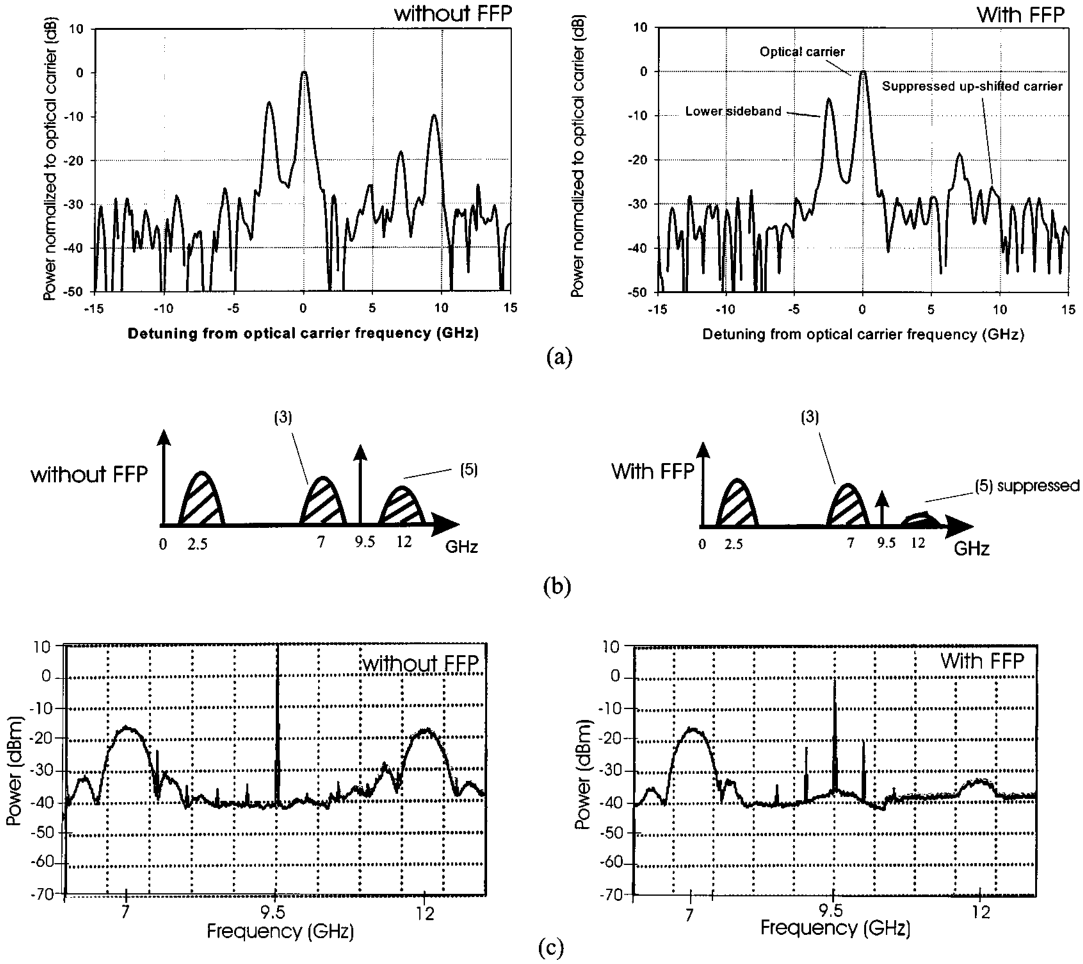

Fig. 3. Receiver performance in the case of purely LSB signals. (a) Optical spectra after the DE–MZM both with and without the use of FFP. Note the up-shifted carrier suppression when the FFP is used. (b) Projected microwave spectra, as obtained from Table I, after heterodyning in the photodetector. (c) Measured microwave spectra showing the suppression of the unwanted term at 12 GHz when the FFP is used.

10 GHz and a finesse of 200 operating in reflection mode. A feedback loop keeps the FFP locked to the up-shifted carrier wavelength. This has the effect of suppressing terms (5)–(8), thus enabling the error-free recovery of the LSB and USB from terms (3) and (4), respectively. We may thus conclude that terms (3) and (4) are very desirable to us, while terms (5) and (6) are undesirable. We will use this notion in the remainder of our discussions. Note that we do not really care about terms (1), (2), (7), and (8) since they all appear at f_1 GHz and we have no way of distinguishing between them.

The signal reflected from the FFP was amplified by an erbium-doped fiber amplifier (EDFA) and then detected by an Agilent Lightwave Converter 11982A with a conversion gain of 300 V/W. No other electrical amplification was used. The output was connected to a bandpass filter (BPF) centered at (f_1+f_2) GHz, followed by two stages of microwave down-conversion to bring the signal back to baseband. The RF LOs used for down-conversion were exactly those used for up-conversion, enabling exact phase and frequency matching. In practical systems where the transmitter and receiver are far apart, the RF carrier can be recovered through the use of a Costas loop [11]. The baseband signal was connected to a 500-MHz low-pass filter (LPF), followed by a digital oscilloscope (HP 54542C) to monitor eye diagrams, and an error performance analyzer to measure bit error ratio (BER).

III. Results and Discussion

In order to test our design, we used $f_{oc} = 193.7$ THz, $f_1 = 2.5$ GHz, and $f_2 = 9.5$ GHz with different 500-Mb/s PRBS data on each sideband. The 90° hybrid couplers used in the experiment did not go all the way down to dc, thus restricting us to a minimum f_1 of 2.5 GHz. The bandpass nature of the hybrid coupler places a limitation on the ultimate achievable spectral efficiency, but this wastage of bandwidth is constant regardless of the number of subcarriers used, suggesting that the spectral efficiency can be improved by using more subcarriers.

We first tested the receiver with a pure LSB, obtained by connecting a signal only to input A at the transmitter. The optical spectrum entering the receiver consisted of an optical carrier at $f_{oc} = 193.7$ THz, and an LSB at $(f_{oc} - 2.5)$ GHz. Fig. 3(a) shows that the DE–MZM at the receiver had the effect of creating an up-shifted copy of the spectrum centered at $(f_{oc}+9.5)$ GHz. The optical spectrum was measured immediately after the EDFA both with and without the use of the FFP to suppress the carrier at $(f_{oc} + f_2) = (f_{oc} + 9.5)$ GHz.

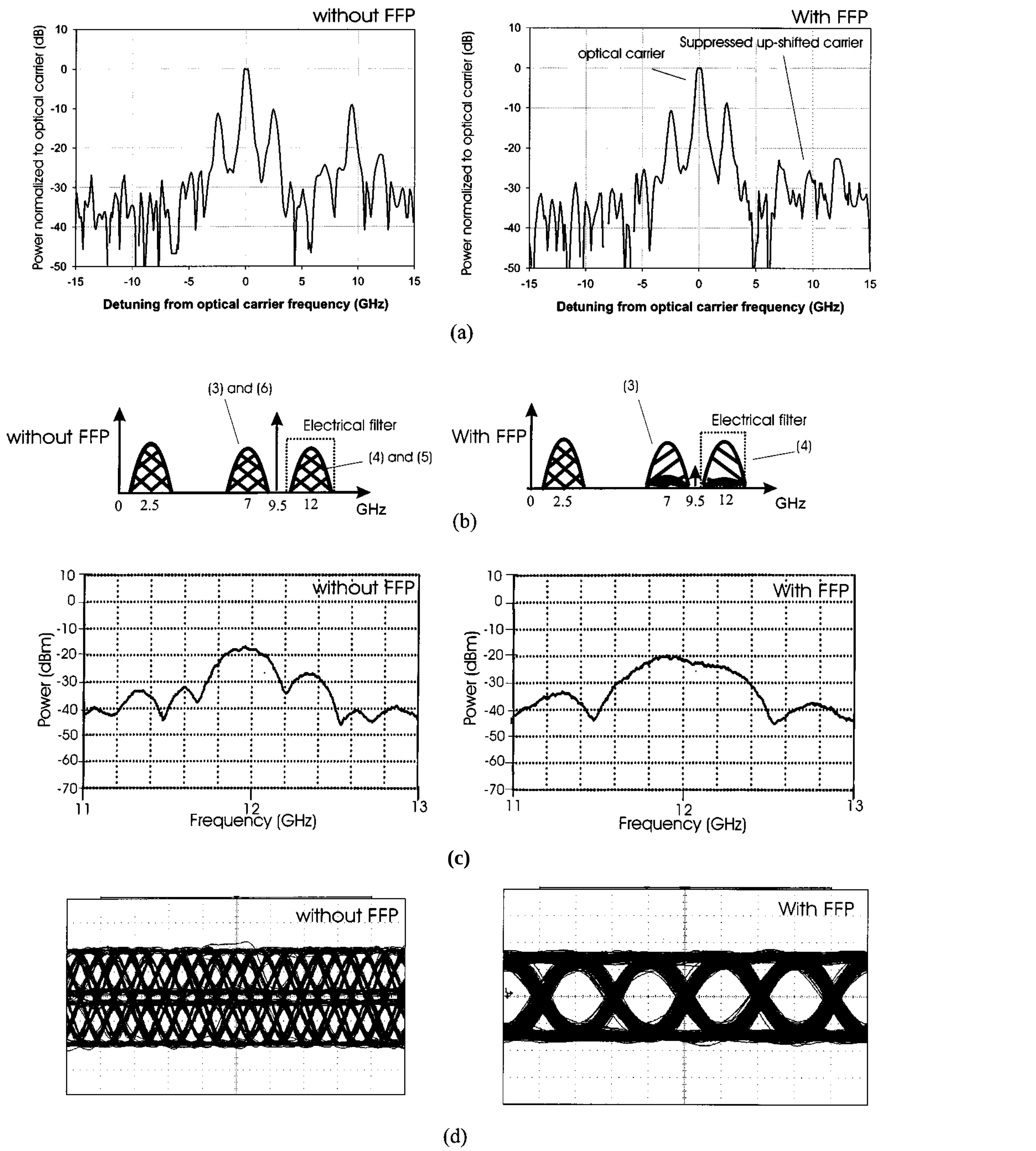

Fig. 4. Receiver performance for the case of TSSB signals. (a) Optical spectra after the DE–MZM both with and without the use of FFP. Note the up-shifted carrier suppression when the FFP is used. (b) Projected microwave spectra, as obtained from Table I, after heterodyning in the photodetector. (c) Measured microwave spectra showing that the use of the FFP enables undistorted recovery of the USB data at 12 GHz. (d) Eye diagrams of the signal at 12 GHz for both cases. A good eye diagram is obtained when the FFP is used.

Fig. 3(b) shows the predicted microwave spectra based on Table I for the optical spectra shown in Fig. 3(a). Table I suggests that only the odd-numbered terms would be present after the photodetector, while the even-numbered terms would be absent since there is no USB. Thus, any signal appearing at 12 GHz would be solely due to term (5), since term (4) would be absent. Tuning the FFP to the up-shifted carrier frequency at $(f_{oc}+9.5)$ GHz would eliminate term (5).

Fig. 3(c) shows measured microwave spectra for these two cases, confirming our predictions. The undesirable LSB term (5) at 12 GHz was suppressed by more than 15 dB.

In Fig. 4, we show the receiver operation for a TSSB signal. This time the incoming optical spectrum consisted of an optical carrier at $f_{oc} = 193.7$ GHz, an LSB at $(f_{oc} - 2.5)$ GHz, and a USB with different data at $(f_{oc}+2.5)$ GHz. Once again, Fig. 4(a) shows the original and up-shifted versions of the TSSB optical spectrum, both without and with the use of the FFP.

Fig. 4(b) shows the expected microwave spectrum for both cases. When the FFP is not used, we would expect all eight heterodyning terms from the photodetector, thus resulting in all sidebands interfered with each other. However, when the FFP is used, we would expect to recover the LSB and USB data from

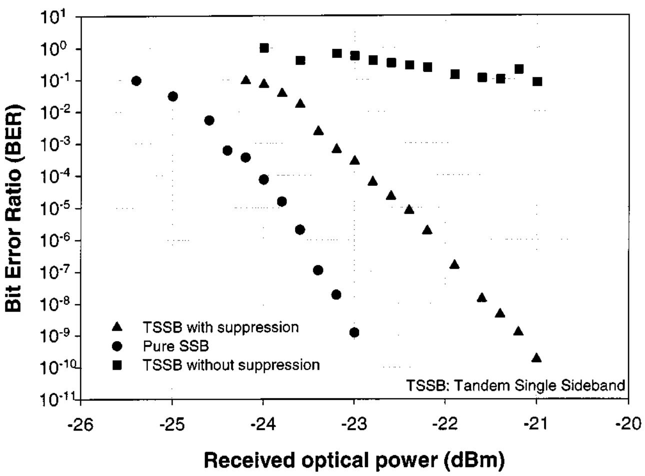

Fig. 5. BER data for the TSSB transmission system for the case of purely SSB transmission, TSSB transmission without up-shifted carrier suppression, and TSSB transmission with up-shifted carrier suppression. A good BER curve is obtained for TSSB signals when the up-shifted carrier suppression is employed.

signals (3) and (4), at 7 and 12 GHz, respectively.

Fig. 4(c) shows the measured microwave spectra of the signal at 12 GHz. When the FFP was not used, the PRBS spectrum was severely distorted, giving us a strongly interfered eye diagram in Fig. 4(d) and confirming our reasoning. Notice that the distortion of the spectrum was minimal when the FFP was used, resulting in an excellent eye diagram in Fig. 4(d).

Fig. 5 shows BER data for the case of pure SSB transmission and TSSB transmission both with and without up-shifted carrier suppression. When the up-shifted carrier is suppressed, a good BER curve is obtained; however, there is a power penalty of a little less than 2 dB in comparison to the pure SSB case. We think that this is probably due to the imperfect suppression of the up-shifted carrier and may be improved by using an FFP with greater contrast in the reflection mode.

In all of the above cases, sharp microwave filtering is used to distinguish between terms (3) and (4) , or the LSB and USB, enabling the system to tolerate the slow rolloff present in optical filtersd, thus eliminate guardbands.

IV. Conclusions

We have successfully demonstrated a TSSB receiver that achieves a heterodyning function without the use of an optical LO and its associated complexities. This could lead to the realization of other applications that up to now required an optical LO to implement.

TSSB modulation increases the capacity of a single wavelength by transmitting different data in the two sidebands of the same optical carrier. The scheme provides for doubling the capacity on a single wavelength without requiring an increase in modulator bandwidth. This enhances the potential of SCM as a broadcast tool and may be useful for wavelength routing schemes since it increases the channel throughput [12]. TSSB modulation doubles the spacing between optical carriers without needing guardbands, making this an effective scheme to increase the overall spectral efficiency of a WDM system, while also providing immunity from dispersion penalties.

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