Full optical spectral utilization by microwave domain filtering of *tandem* single sidebands

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Abstract: We present an optical *tandem* single sideband receiver that eliminates the need for guardbands between adjacent WDM channels, while also receiving signals that have different data on the two sidebands of the same optical carrier.

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1. Introduction

There is a great deal of interest in optical single sideband (OSSB) communication systems on account of their ability to reduce the dispersion penalty while increasing the spectral efficiency of optical communications channels [1]. Recently we demonstrated a *tandem* single sideband modulation scheme, which increases the spectral efficiency and improves the flexibility of an optical communication system by transmitting different information in both sidebands of the same optical carrier [2]. However, any attempt at using simple optical filtering to separate the sidebands from each other would result in wastage of spectral space owing to the huge guard bands that would have to be left between the sidebands and the optical carrier to allow for the slow roll-off present in optical filters. The slow roll-off also requires the use of large guard bands between adjacent optical channels in a WDM spectrum.

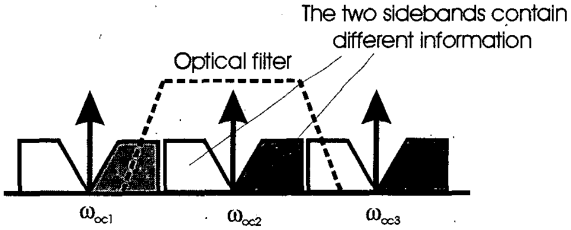

Fig. 1 The *tandem* single sideband receiver design eliminates the need for guard bands between optical channels. An optical channel may be extracted by coarse optical filtering since the sidebands are finally separated by sharp filters in the electrical domain, thus eliminating any cross talk from neighboring channels.

We present an optical receiver that simultaneously eliminates the need for guard bands between adjacent optical channels and enables the error-free reception of spectrally dense optical signals that contain different information in the upper and lower sidebands (USB and LSB) of the same optical carrier (Fig. 1). The receiver uses a combination of a dual-electrode Mach-Zehnder modulator and a Fiber Fabry Perot in reflection mode to allow it to receive signals from a densely packed optical spectrum. Microwave filtering is used for the ultimate separation of the sidebands. Since the sharp filtering requirement is met in the electrical domain, a relatively coarse optical filter such as the one in Fig. 1 may be used to separate the adjacent optical channels.

2. Experimental Arrangement and Principle of Operation

Fig. 2 shows a block diagram of the experimental setup. To demonstrate our receiver we generated tandem single sideband signals (signals with different data on each sideband) using a transmitter such as the one described in [2]. The light source was an external cavity tunable laser diode (ECT-LD), tuned to an optical frequency f_{oc} GHz. The light was coupled into a dual-electrode Mach-Zehnder modulator (DE-MZM) through a polarization controller. An externally triggered pattern generator with $2^{23} - 1$ pseudo random bit sequences provided the two base band signals which were used to modulate a sub-carrier frequency of f_1 GHz. using BPSK. The two signals were then fed to the two inputs of a 90-degree hybrid coupler as shown in Fig. 2. The outputs of the 90-degree hybrid were connected to the two electrodes of a dual-electrode Mach-Zehnder modulator (DE-MZM) through bias-Ts. The DE-MZM was biased at quadrature. Tandem single sideband transmission could be achieved by connecting different signals to the two inputs of the 90-degree hybrid [2]. The two sidebands appear at (f_{oc}-f_1) and (f_{oc}+f_1) GHz. At the receiver, the tandem single sideband spectrum was first up-shifted by f_2 GHz, using another dual-electrode Mach-Zehnder modulator (DE-MZM) as shown in Fig. 2. This DE-MZM was also biased at quadrature. Since the upper single sideband input of the DE-MZM was used, only an up-shifted version of the spectrum appeared, while the downshifted version was rejected [1, 2].

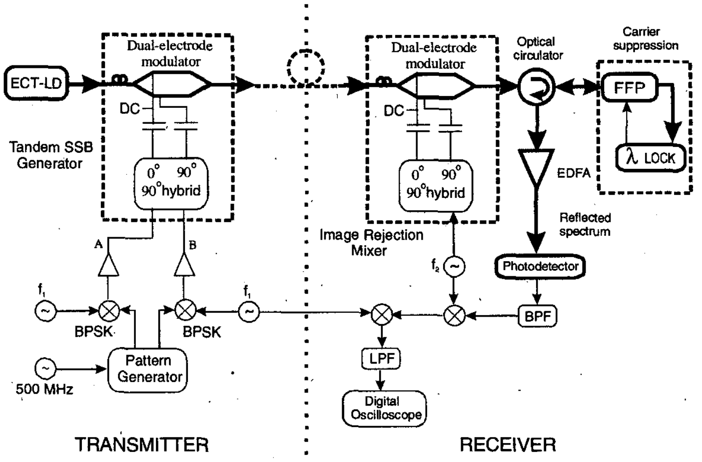

Fig. 2 Block diagram of highly spectrum efficient, *tandem* single sideband receiver

The optical spectrum now consisted of the original tandem single sideband spectrum centered at f_{oc} GHz and a copy of it centered at (f_{oc}+f_2) GHz. The up shifted carrier at (f_{oc}+f_2) GHz was suppressed using a Fiber Fabry Perot in reflection mode. This was essential to eliminate cross talk as will be seen shortly. The reflected signal was amplified by an Erbium Doped Fiber Amplifier (EDFA) and then detected by a photodetector (HP Lightwave Converter 11982A) with a responsivity of 300 V/W for a 50 Ω load. The output of the photodetector was connected to a band pass filter (BPF) centered at (f_1+f_2) GHz, followed by two stages of microwave down-conversion to bring the signal back to base band. Eye diagrams were observed on a digital oscilloscope (HP 54542C).

When the signal enters the photodetector, the original carrier at f_{oc} GHz acts as a local oscillator to produce 4 principal beating terms at separate intermediate frequencies [3]. The four IF signals were obtained from the beating of:

1. Carrier at f_{oc} GHz with sideband at (f_{oc}-f_1) GHz yielding LSB at f_1 GHz
2. Carrier at f_{oc} GHz with sideband at (f_{oc}+f_1) GHz yielding USB at f_1 GHz
3. Carrier at f_{oc} GHz with up-shifted sideband at (f_{oc}+f_2-f_1) GHz yielding LSB at (f_2-f_1) GHz
4. Carrier at f_{oc} GHz with up-shifted sideband at (f_{oc}+f_2+f_1) GHz yielding USB at (f_2+f_1) GHz

The upper and lower sidebands are then obtained at distinct intermediate frequencies of (f_2+f_1) and (f_2-f_1) GHz (terms 3 and 4) respectively.

In the absence of the Fiber Fabry Perot, that enabled the up shifted carrier suppression, four additional signals would be seen at intermediate frequencies. This is due to the presence of the up shifted carrier at (f_{oc}+f_2) GHz that also acts as a local oscillator. The four additional IF signals obtained are:

5. Up-shifted carrier at (f_{oc}+f_2) GHz with lower sideband at (f_{oc}-f_1) GHz yielding LSB at (f_2+f_1) GHz
6. Up-shifted carrier at (f_{oc}+f_2) GHz with upper sideband at (f_{oc}+f_1) GHz yielding USB at (f_2-f_1) GHz
7. Up-shifted carrier at (f_{oc}+f_2) GHz with up-shifted sideband at (f_{oc}+f_2-f_1) GHz yielding LSB at f_1 GHz
8. Up-shifted carrier at (f_{oc}+f_2) GHz with up-shifted sideband at (f_{oc}+f_2+f_1) GHz yielding USB at f_1 GHz

Clearly the pairs of signals, 3 and 6 as well as 4 and 5 interfere with each other by appearing at the same intermediate frequency. Thus we cannot separate the two sidebands effectively if all of the above eight IF signals appear. In order to obtain only the first four signals we need the up shifted carrier suppression.

3. Results and Discussion

For our demonstration we used f_{oc}=193.7 THz, f_1=2.5 GHz and f_2=9.5 GHz with different 500 Mbps PRBS data on each sideband. The dual-electrode Mach-Zehnder modulator connected in the configuration shown in Fig. 2 had the effect of up shifting the optical spectrum while suppressing the downshifted version [1, 2]. We performed the experiment both with and without the up-shifted carrier suppression.

In Fig. 3a, we show the case of no up-shifted carrier suppression. Eight IF terms resulted at the photodetector as described above, with the carriers at f_{oc} GHz and $(f_{oc}+f_2)=(f_{oc}+9.5)$ GHz serving as local oscillators. The recovered signal at the intermediate frequency of $(f_1+f_2)=(2.5+9.5)=12$ GHz consisted of terms 4 and 5 together. Terms 4 and 5 contained different data since they came from the upper and lower sidebands respectively. The measured eye diagram is severely interfered, confirming our reasoning.

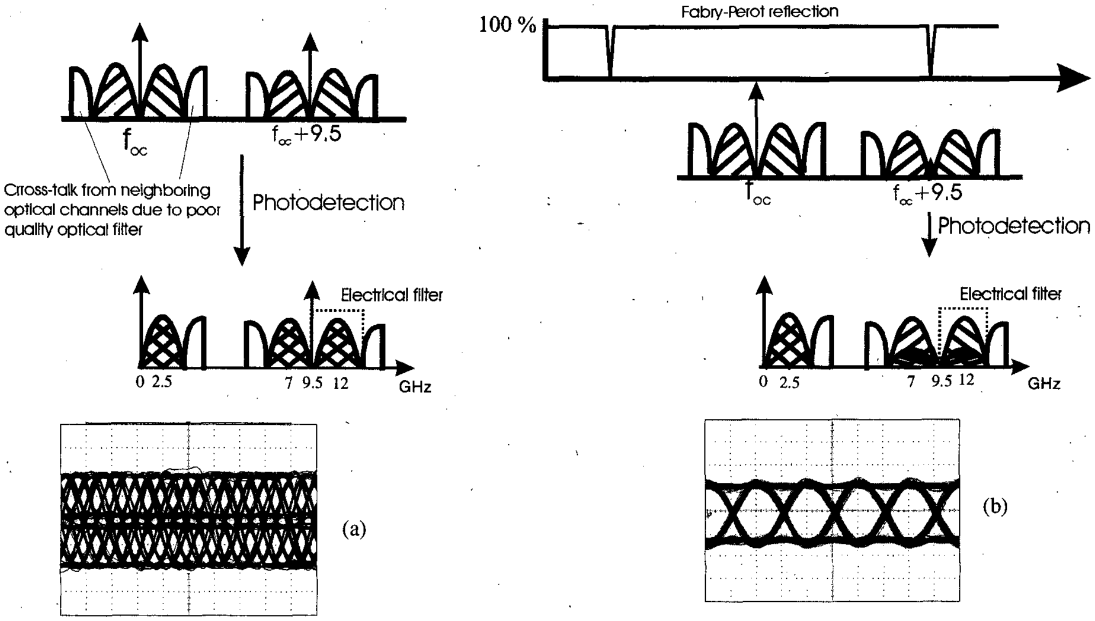

Fig.3 Expected optical and microwave spectra along with the measured eye diagram at 12 GHz for the case of a) no up-shifted carrier suppression and b) carrier at $(f_{oc}+9.5)$ GHz suppressed. The carrier suppression canceled all interfering terms resulting in an excellent eye diagram in b. Cross-talk from neighboring optical channels was rejected by the sharp electrical band pass filter

Fig. 3b shows the case when the up-shifted carrier is suppressed, thus also suppressing terms 5-8. The recovered signal at 12 GHz consisted only of term 4, and the USB data could be recovered as is indicated by the well-opened eye diagram.

Notice from Fig. 3 that the cross talk from adjacent wavelength channels appeared at separate intermediate frequencies and was rejected by the sharp electrical band pass filter.

4. Conclusions

The results above demonstrate the working of the highly spectrum efficient tandem single sideband receiver. We achieved the error-free reception of the tandem single sidebands through the use of a DE-MZM, a Fiber Fabry Perot in reflection mode, and sharp microwave filters. The system works even in the presence of cross-talk caused by the poor roll-off present in the optical filter, since all cross-talk is rejected by the sharp electrical band pass filter. We have thus demonstrated the reception of tandem single sideband signals in a densely packed optical spectrum.

References

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