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Tandem single sideband modulation scheme for doubling spectral efficiency of analogue fibre links

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Using a dual-electrode Mach-Zehnder modulator, a 'tandem' single sideband modulator has been constructed that doubles the spectral efficiency of a system by enabling the transmission of different data streams in the upper and lower sidebands of the same optical carrier.

Introduction: Optical single sideband (SSB) modulation has received a great deal of attention recently as a method for reducing the dispersion penalty of analogue fibre optic systems [1, 2]. The 'tandem' approach presented in this Letter modifies this concept by allowing different information to be transmitted in each sideband of the same optical wavelength, thus doubling the information-carrying capacity. Tandem SSB carriers are spaced twice as far apart than in SSB systems, which makes them easier to reject by microwave filtering than in the conventional SSB case.

In this Letter, we demonstrate, for the first time to our knowledge, the transmission of two different data streams on the two sidebands of the same optical carrier. The transmitter was built using an $LiNbO_3$ dual electrode Mach-Zehnder modulator.

Experimental setup: Fig. 1 shows the experimental setup. The light source was an external cavity tunable laser diode (ECT-LD), tunable around 1550nm. The light from the ECT-LD was coupled into a dual electrode Mach-Zehnder modulator (DE-MZM) through a polarisation controller. An externally triggered pattern generator with $2^{23} - 1$ pseudorandom bit sequences provided the two baseband signals. The data was modulated using binary phase shift keying (BPSK) onto a sub-carrier at a frequency f_c = 7GHz. The power in each of the two arms, A and B, was 17dBm. The two signals were then fed to the two inputs of a 90° hybrid coupler. The outputs of the 90° hybrid were used to drive the DE-MZM through bias-Ts. The DE-MZM was biased at quadrature. An erbium-doped fibre amplifier (EDFA) was used to boost the output optical power. At the receiver, both the upper and the lower sidebands were separated by a combination of an optical circulator (OC) and a reflective fibre grating (FBG filter) with a full width half maximum of 20GHz centred at ~193.7THz (Fig. 2). The signal was detected by a photodetector (HP lightwave converter 11982A) with a responsivity of 300V/W for a 50Ω load. The output was connected to a lowpass filter (LPF) followed by a digital oscilloscope (HP 54542C) to monitor the eye diagrams.

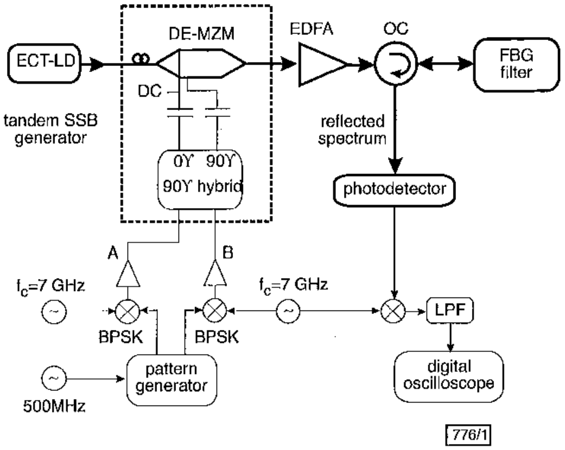

Fig. 1 *Experimental setup of tandem SSB modulator*

—— optical
—— RF

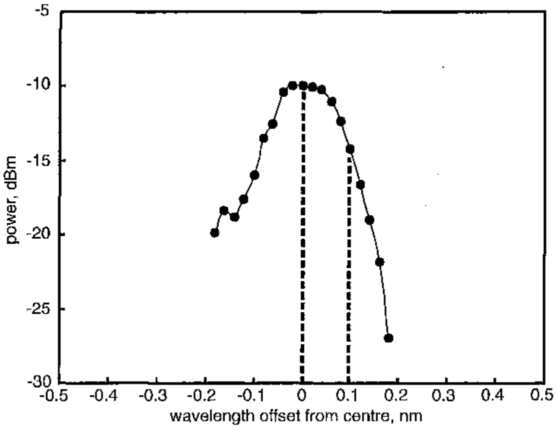

Fig. 2 *Spectral response of fibre grating filter*

···· wavelengths at which experiment was performed
Full width half maximum = 20GHz, centre frequency = 193.7THz

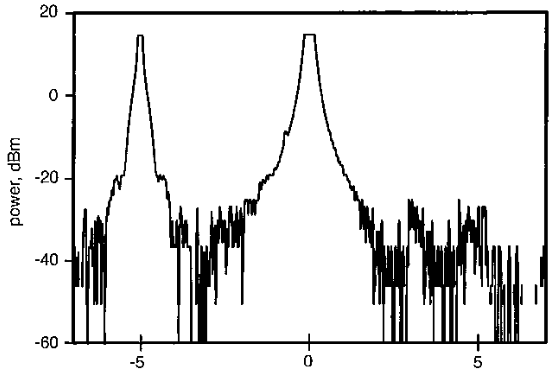

Fig. 3 *Sideband rejection obtained from dual-electrode Mach-Zehnder modulator*

The setup was used to transmit only one sideband while suppressing the other one by connecting a signal to only one of the two inputs of the 90° hybrid. Tandem single sideband operation was achieved by connecting different signals to each of the two inputs of the 90° hybrid.

Results and discussion: Fig. 3 shows the sideband suppression obtained from the dual-electrode modulator. As a preliminary test, a pure RF frequency of 5GHz was connected to input B of the 90° hybrid, with no signal at input A. As can be seen in Fig. 3, the modulator suppressed the upper frequency sideband by more than 30dB.

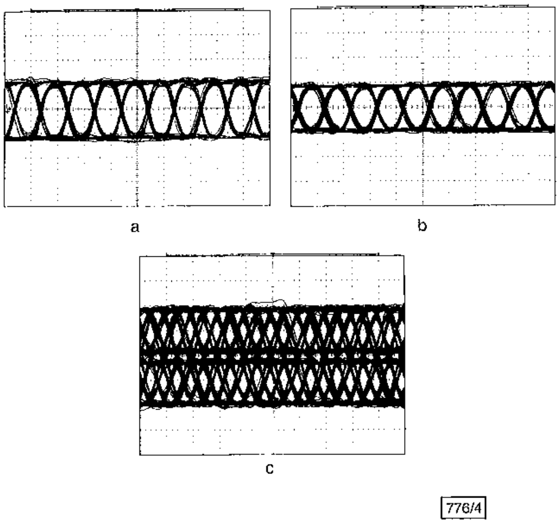

Fig. 4 *Received eye diagrams when both sidebands were reflected by fibre grating filter into photodetector*

a Upper frequency sideband only transmitted
b Lower frequency sideband only transmitted
c Both sidebands transmitted in tandem

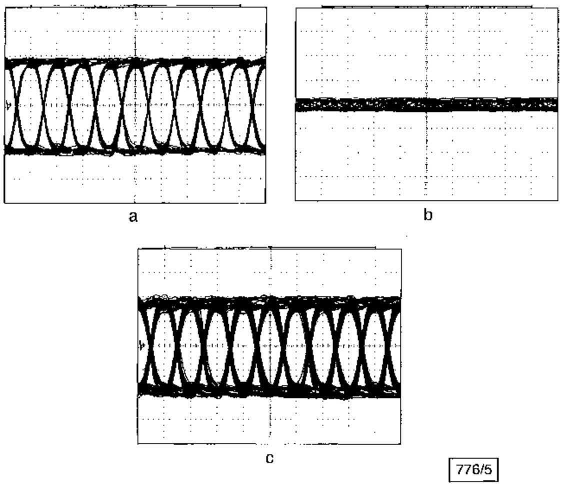

Fig. 5 *Received eye diagrams when only upper frequency sideband was reflected by fibre grating filter into photodetector*

a Upper frequency sideband only transmitted
b Lower frequency sideband only transmitted
c Both sidebands transmitted in tandem

The actual experiment was performed at two different wavelengths of the laser source. In the first case, the laser frequency was chosen to correspond with the centre frequency of the fibre grating (0nm in Fig. 2). This ensured that both sidebands were almost equally reflected by the fibre grating filter. Fig. 4*a* shows the received eye diagram for the case of a signal connected to input A of the 90° hybrid, with no signal at input B, thus placing the signal on the upper frequency sideband and suppressing the lower frequency sideband. Fig. 4*b* shows the eye diagram for the opposite case with a signal only at input B of the 90° hybrid, thus placing the signal on the lower frequency sideband while suppressing the upper one. Figs. 4*a* and *b* show that the upper and lower sidebands were almost equally reflected by the fibre grating, and that the transmission was successful when they were transmitted individually. Fig. 4*c* shows the received eye diagram for the case when different signals were connected to both inputs A and B of the 90° hybrid coupler, thus transmitting the two optical sidebands in tandem. The severely degraded eye diagram indicates that there were different pseudorandom signals on each of the sidebands.

The experiment was repeated with the laser frequency downshifted by 12GHz. At 193.7THz, this corresponds to a wavelength upshift of ~0.1nm as shown in Fig. 2. Figs. 5*a* and *b* show the cases when the sidebands were transmitted individually. The fibre grating reflected the higher frequency (lower wavelength) sideband, while almost completely rejecting the lower frequency (higher wavelength) sideband, as can be seen from Figs. 5*a* and *b*. The rejection of the lower frequency sideband resulted in an excellent eye diagram in Fig. 5*c*, even when both sidebands were transmitted in tandem.

The observation that there were different signals in the upper and lower sidebands shows that the tandem transmission was successful. We have thus demonstrated a doubling of the spectral efficiency by transmitting different information in each of the two sidebands.

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All-electronic high-speed programmable wavelength tuning of picosecond optical parametric oscillator

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A method for achieving high-speed, all-electronic, and freely programmable wavelength tuning of a synchronously diode-pumped OPO, which is capable of generating more than 100000 different wavelengths per second, is presented.

Synchronously pumped (SP) singly-resonant optical parametric oscillators (SROs) are known as widely tunable sources of ultrashort pulses in the near and mid infrared wavelength range [1, 2]. Pump sources are usually continuous-wave modelocked solid-state lasers which provide pump pulses with picosecond or femtosecond pulse duration, and with a standard repetition rate of ~80MHz. Synchronous pumping of the SRO is achieved by choosing the length of its cavity such that the roundtrip time for the resonant SRO wave matches the repetition rate of the pump pulses.

The desired wavelength of an SP-SRO is generally selected by an appropriate tuning of the phase matching wavelength in the nonlinear crystal. This can be done, for example, by varying the temperature of the nonlinear crystal, although this results in a relatively slow tuning of the SRO with time constants of a few seconds.

In this Letter we describe a new, all-electronic method of SP-SRO tuning which provides an up to 6 order of magnitude faster tuning speed and enables freely programmable wavelength access. So far, we have generated more than 100000 different signal and idler wavelengths per second.

Wavelength tuning of our SP-SRO operates as follows. First a