50km error-free 10Gbit/s WDM transmission using directly modulated long-wavelength VCSELs


The first long-wavelength VCSEL based WDM link over a distance of 50km is demonstrated. Error-free transmission at a speed of 10Gbit/s is achieved over 50km of standard singlemode fibre. The link comprises four individually modulated L-band VCSELs each transmitting at a speed of 2.5 Gbit/s. No crosstalk is observed between channels. Our system is suitable for deployment in metro networks where low cost combined with high data rates are paramount.

Currently 850nm vertical cavity surface emitting lasers (VCSELs) have gained commercial acceptance as highly reliable, cost-effective transmitters for high-speed optical communications [1]. However, the emergence of VCSEL technology which is applicable to the long-distance market has been slower to mature. This is in part due to the poorer optical properties of the InAlGaAs materials in the 1.3-1.6μm wavelength range. We recently reported the development of a new 1.6μm monolithic VCSEL and demonstrated CW operation and 2.5Gbit/s data transmission at room temperature [2]. We demonstrated error-free transmission over 50km of dispersion-shifted Corning LEAF fibre, with a power penalty of < 1.5dB at a speed of 2.5Gbit/s. In this Letter we demonstrate the first wavelength division multiplexed system with error-free transmission over 50km of optical fibre at an aggregate data rate of 10Gbit/s.

The VCSEL devices used in the WDM system comprised n-doped InAlGaAs/InAlAs bottom DBRs, with an InGaAs multiple quantum well active region, lattice matched to the InP substrate. The p-type top mirror was metamorphic GaAs/AlGaAs. Current and optical confinement were provided by selective oxidation. Typical singlemode output powers are ~0.2mW with a lasing threshold of < 2mA and a series resistance of <200Ω. High coupling efficiencies of > 90% into singlemode fibre have also been demonstrated.

Fig. 1 shows a schematic diagram of the 10Gbit/s WDM system. Four VCSELs were used to transmit 2.5Gbit/s data streams on separate optical channels on an 800GHz grid spacing. The VCSELs were selected with emission wavelengths of 1581.04, 1588.10, 1594.39 and 1601.51 nm. Independent DC current sources were used to bias the lasers such that the output power was half of the maximum singlemode power. A bias-tee was used to combine the DC and RF drives from the bit error rate tester. The modulation level was adjusted with separate step attenuators to achieve an extinction ratio of greater than 10dB. Independent pseudorandom data streams each with a rate of 2.5Gbit/s and a word length of 2^23 – 1 were applied to each laser separately. Optical isolation of the lasers was achieved with in-line optical fibre isolators. Under these modulation conditions, the extinction ratio was measured typically to be >10dB, with a peak chirp of ~10GHz.

The multiplexing and demultiplexing of the optical channels was performed with a WaveSplitter Technologies MUX/DEMUX pair [3] using a channel spacing of 6.4nm. The multiplexed signals were launched into 50km of conventional singlemode optical fibre. Detection of the demultiplexed signals was achieved with commercial avalanche photodiodes (APDs) with a sensitivity of -32dBm.

Fig. 2 shows the insertion loss of the MUX/DEMUX in series (dashed lines) and a spectra of the combined lasers which were launched into the 50km span (solid). The fused fibre coupler design of the MUX/DEMUX causes the channels to be periodically repeated every 32nm, and also permits low insertion loss and a wide 1dB bandwidth of >2nm. Typically our VCSELs exhibit sidemode suppression ratios > 30dB, as is the case for channels 1–3. The satellite peak to the blue side of channel 4 is the first excited transverse mode of the VCSEL, however we do not observe any inferior performance of this channel caused by the additional mode.

Fig. 3 shows the bit error rate curve for a single channel after transmission through 50km of SMF-28 fibre, with all lasers transmitting simultaneously at an aggregate rate of 10Gbit/s (circles, eye diagram inset (a)). All four channels exhibit BERs of < 10^-9, and have comparable error performance as the received power is attenuated. No error floor is observed for any of the channels. If we transmit on a single channel only, with the other lasers off, an identical BER curve is measured (triangles). This indicates there is no crosstalk between channels, as there is no difference in BER for single- or multi-channel transmission.

The solid diamond points show the results of a back-to-back measurement of a single channel, and the system transmission power penalty is measured to be 3.7dB at 10^-9 BER. The corresponding eye-diagram in shown in Fig. 3, inset (b). The difference in slope of the back-to-back BER characteristic is attributed to dispersion in the fibre (21nm/ps.km). Furthermore, the insertion of the MUX/DEMUX stages into the system has no measurable power penalty.

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**Fig. 1** System diagram

T indicates bias-Tees, λ1–λ4 denote the individual WDM channels

**Fig. 2** MUX+DEMUX insertion loss and laser spectra

- - - - insertion loss curves for different MUX+DEMUX channels

launched multiplexed optical power in fibre from four VCSELs

**Fig. 3** BER curves and eye diagrams

- back-to-back link

○, △ four-channel and single-channel transmission curves

Insets

a) Eye diagram for four-channel 50km transmission

b) Single-channel back-to-back transmission

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Conclusion: We have demonstrated the first 10Gbit/s 50km WDM link based upon a new long-wavelength VCSEL. The link consists of four channels modulated at 2.5Gbit/s and has a 3.7dB power penalty at a BER of 10^-9 compared to back-to-back transmission. We measure BERs of < 10^-9 for all channels simultaneously at a word length of 2^31 - 1. No effect of crosstalk is observed between channels. Our VCSEL transmitters have peak chirp of 10GHz at a 10dB extinction ratio.

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PRINCIPLES OF OPERATION


Introduction: In future WDM networks, all-optical wavelength conversion will be an important functionality and, consequently, the development of practical wavelength converters has attracted considerable attention. A promising conversion technique uses cross-phase modulation in SOA-based interferometers. This is due to an excellent high-speed performance [1, 2] and regenerative capability [3], where the latter will be essential for future large-scale optical networks. However, a trade-off between speed and transmission properties normally exists in these devices. On the one hand, the highest modulation bandwidth is achieved with inverting operation, i.e. the polarity of the converted signal is inverted compared to the input signal. This, however, results in a chirped signal, causing degradations on standard fibre. On the other hand, non-inverting operation has a lower modulation bandwidth but results in a signal with good transmission properties.

Here, we experimentally demonstrate that by using a novel conversion principle in SOA-based interferometric devices both good transmission quality and high-speed performance can be achieved simultaneously.

Principle of operation: An illustration of the conventional and novel scheme for wavelength conversion in interferometric devices is given in Figs. 1a and b, respectively. In the conventional scheme (Fig. 1a), a data and CW signal is coupled into the interferometer as shown, resulting in an inverted or non-inverted signal at \( \lambda_{\text{CW}} \) (non-inverted in Fig. 1a). In the novel scheme (Fig. 1b) an additional clock signal, synchronised to the data signal and with a repetition rate corresponding to the bit rate, is injected into the lower interferometer arm and, as in the conventional scheme, the wavelength-converted signal of interest is at \( \lambda_{\text{CW}} \). Here, inverting or non-inverting operation is also possible, although the appearance of the converted signal is different. When a logical '1' is present in the data signal, i.e. the clock and data signals are identical, the CW light will experience equal phase conditions in the interferometer arms, resulting in a constant output power. On the other hand, with a '0' in the data signal, the interferometer will be unbalanced, resulting in a pulse at the output, which is entirely determined by the clock signal. Fig. 1b shows an inverted signal. We note that, even though a Mach-Zehnder is shown, the novel scheme is also applicable for a Michelson device.

![Fig. 1 Illustration of two techniques for wavelength conversion in SOA-based interferometric devices](image_url)

**Fig. 1.** Illustration of two techniques for wavelength conversion in SOA-based interferometric devices

- a Conventional scheme
- b Novel scheme

![Fig. 2 Eye diagrams of converted signals at 10Gbit/s using conventional and proposed schemes](image_url)

**Fig. 2.** Eye diagrams of converted signals at 10Gbit/s using conventional and proposed schemes

- a Back-to-back
- b Conventional scheme (not inverted)
- c Conventional scheme (inverted)
- d Proposed scheme (inverted)

Experimental results and discussion: The speed performance of the two conversion schemes is illustrated in Fig. 2, showing eye-diagrams of the back-to-back signal (Fig. 2a) and the converted signal using the conventional scheme (non-inverted in Fig. 2b and...