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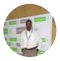
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A 1550 nm All-Optical VCSEL-to-VCSEL Wavelength Conversion of a 8.5 Gb/s Data Signal and Transmission over a 24.7 km Fibre

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ABSTRACT

For the first time, we demonstrate, VCSEL-to-VCSEL wavelength conversion within the low attenuation 1550 nm transmission window, including transmission over fibre and bit error rate (BER) performance characterization. We experimentally demonstrate a low injection power optical wavelength conversion by injecting an optical beam from a signal carrier master vertical cavity surface-emitting laser (VCSEL) into the side-mode of the slave VCSEL. This technique solves the challenge of wavelength collisions and also provides wavelength re-use in typical wavelength division multiplexed (WDM) systems. This paper, for the first time, uses two 1550 nm VCSELs with tuneability range of 3 nm for a 5-9.8 mA bias current. The master VCSEL is modulated with a non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS_2^7-1) 8.5 Gb/s data. A data signal conversion penalty of 1.1 dB is realized when a 15 dBm injection beam is used. The transmission performance of the converted wavelength from the slave VCSEL is evaluated using BER measurements at a 10^{-9} threshold level. A 0.5 dB transmission penalty of the converted wavelength data is realized in an 8.5 Gb/s transmission over 24.7 km. This work is vital for optical fibre systems that may require wavelength switching for transmission of data signals.

Keywords- VCSELs, wavelength Conversion, data signals, fibre links

1. INTRODUCTION

Optical fibres form the backbone of modern long haul signal transmission. An efficient and effective way of utilizing an optical fibre link is to transmit multiple wavelength signals. This is done by utilizing wavelength division multiplexing (WDM) technique which is a unique way of distinctively adding new wavelengths into an optical fibre network. In a typical optical network, wavelength collisions can be overcome by utilizing flexible wavelength converters. A combination of purely optical wavelength conversion and the WDM technology can therefore be used to efficiently utilize the available spectrum without necessarily requiring extra bandwidth for users whenever wavelength collisions do occur [1]. Several methods of wavelength conversion have previously been reported and documented and these include: Optoelectronic converters, laser converters and coherent converters [2]. All optical wavelength converters include nonlinear optical gating based on fibre loop, cross-gain modulation, cross-phase modulation and four-wave mixing based on semiconductor optical amplifiers [3]. A key feature of optical wavelength conversion is laser tuneability. Different tuneable sources have been previously used: micro-electro mechanical external cavity diode lasers (MEM-ECL), multi-section DFB lasers and MEM-VCSEL. However, it has been reported that achieving wavelength conversion using MEM-ECL or MEM-VCSEL is difficult since external optical injection to the laser cavity is impossible [4]. A 1310- 1550 nm VCSEL up conversion has been demonstrated [5]. However, the 1310 nm does not fall on the dense-WDM ITU-T grid [6] transmission window due to the high optical attenuation and wide bandwidth range. It is therefore not ideally suited for data and signal WDM transmission over long distances.

This paper reports a purely optical wavelength up conversion based on optically injecting the side-mode of a VCSEL with another VCSEL. The VCSEL laser cavity is current-driven and its wavelength can be tuned [7]. In this scheme, a modulated master VCSEL has been injected into the side-mode of a slave VCSEL. Laser gain saturation due to increased injected

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power is the principle technique for optical conversion [2]. We demonstrate for the first time to the best of our knowledge, an all VCSEL-to-VCSEL optical wavelength conversion at the low attenuation 1550 nm transmission window, which is the lower of the two attenuation windows in optical fibre transmission. We further, illustrate data conversion and inversion from an initial to a new converted wavelength and for the first time characterize the signal by performing BER characteristics with transmission at 8.5 Gb/s over a 24.7 km fibre.

2. THEORY

2.1. The VCSEL Technology

Most VCSELs comprise of an active region that is sandwiched between two layers of distributed Bragg reflector (DBR) mirrors. This active region is made up of InGaAs which is the gain medium that receives current from a proton implant or through an oxide aperture [8]. The structure of the VCSEL is as shown in figure 1. The beam emitted from a VCSEL is perpendicular to the active surface. For the proton implanted VCSELs, there is typically one lasing mode at the threshold level. However, lasing can occur at other regions of the active area, with each mode defined by its emission wavelength. The single transverse mode (STM) VCSEL is fabricated by reducing the extent to which the fundamental mode oscillates within the cavity. This is done by reducing the aperture to 5 μm using a lateral oxidation layer [9].

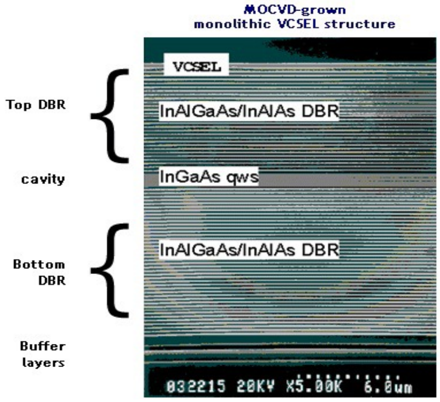

Figure 1: The structure of the VCSEL [10]

A VCSEL is of low power consumption, compact in size, wavelength tuneable, low threshold current, easily coupled circular beam, high speed capability and has a uniform optical-field distribution. These advantages, make the VCSEL an attractive technology for optical systems [11].

3. SYSTEM OF OPERATION: WAVELENGTH CONVERSION

An incident beam of light λ_i from a master laser is injected into the cavity of a multimode secondary (slave) laser. The incident light is injected into the first resonance frequency or the side-mode of the slave laser. During injection, the side-mode is optically stimulated and oscillates within the fundamental gain medium. As a result, the dominant mode of the slave laser is temporally switched “OFF” while the side-mode is switched “ON” during conversion once gain saturation has been attained within the cavity.

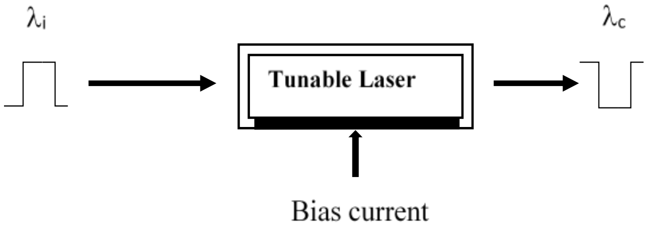

Figure 2: An illustration of an optical wavelength conversion with two lasers [2]

A new lasing wavelength λ_c is created at a converted wavelength and it carries an inverted data signal as shown in figure 2.

4. EXPERIMENTAL SETUP

For the very first time, an experimental demonstration that achieves a purely optical wavelength conversion and transmission based on two 1550 nm VCSELs is shown in figure 3. Two 1550 nm 10 Gb/s VCSELs with a 3.7 nm tuneability range were used to achieve an optical wavelength conversion [12]. VCSEL 1 is the signal carrier master laser, which is modulated at 8.5 Gb/s by a non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS-2^7-1) from a programmable pattern generator (PPG) as shown in figure 3. It was biased at 8.15 mA with a lasing wavelength of 1550.42 nm and an output power of -3.8 dBm. While the slave VCSEL 2 was biased at 8.86 mA with a lasing wavelength of 1551.53 nm and output power of -3.7 dBm. Both VCSELs were biased above the bias mid-points (5.5 mA) to ensure complete modulation and optimum lasing. The biasing currents for both VCSELs were controlled by using a laser diode controller (LDC) through a bias tee (BT).

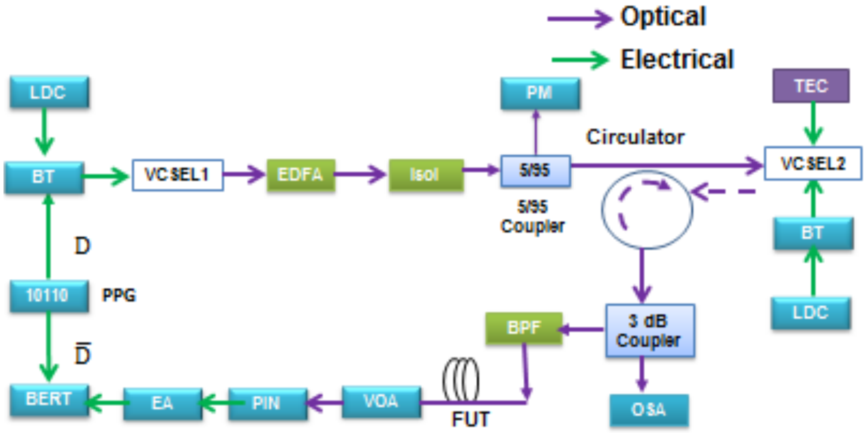

Figure 3: shows an experimental setup for VCSEL-to-VCSEL wavelength conversion with an 8.5 Gb/s transmission over 24.7 km fibre.

The injection power was increased by amplifying VCSEL 1 with an Erbium-doped fibre amplifier (EDFA). Amplification was done so as to provide sufficient optical power for gain saturation within the slave laser cavity. An isolator (Isol) was used to protect the EDFA from the backscattered power. The injected power was monitored using a power metre (PM) via a 5/95 optical coupler. Thereafter, an optical circulator directed the injected beam into the slave laser cavity and the resultant light signal into a 3 dB optical coupler. The temperature of VCSEL 2 was controlled at 25^0C by an external thermoelectric cooler (TEC). Moreover, the dominant mode of VCSEL 2 was filtered through a bandpass filter (BPF) in the form of a wavelength demultiplexer to observe and measure its extinction using an optical spectrum analyser (OSA) or a power meter. The receiver optical power was varied through a variable optical attenuator (VOA) which emulated typical attenuation during transmission. The converted wavelength λ_c was detected by a positive intrinsic negative (PIN) photodiode. An electrical amplifier (EA) was used to amplify the signal so as to meet the operational RF input power requirements of the bit error rate tester (BERT).

Bit error rate (BER) measurements at a threshold of 10^{-9} were done. For the first time, BER was used to determine the quality of the converted data based on an all VCSEL-to-VCSEL optical injection. For data conversion, BER measurement for data (D) transmitted through VCSEL 1 is compared to the inverted data, $(\bar{D})$ as a result of conversion.

To evaluate transmission performance, modulated λ_c is then transmitted over a fibre under test (FUT) to check the integrity and quality of the signal. Two types of fibres were considered; G.652 (Non-dispersion shifted fibre with 17 $ps/nm.km$ dispersion) and G.655 (Non-zero dispersion shifted fibre with 5 $ps/nm.km$ dispersion).

5. RESULTS AND DISCUSSION

The biasing of a VCSEL with increase in current is shown in figure 4 (a), from 0-9.8 mA.

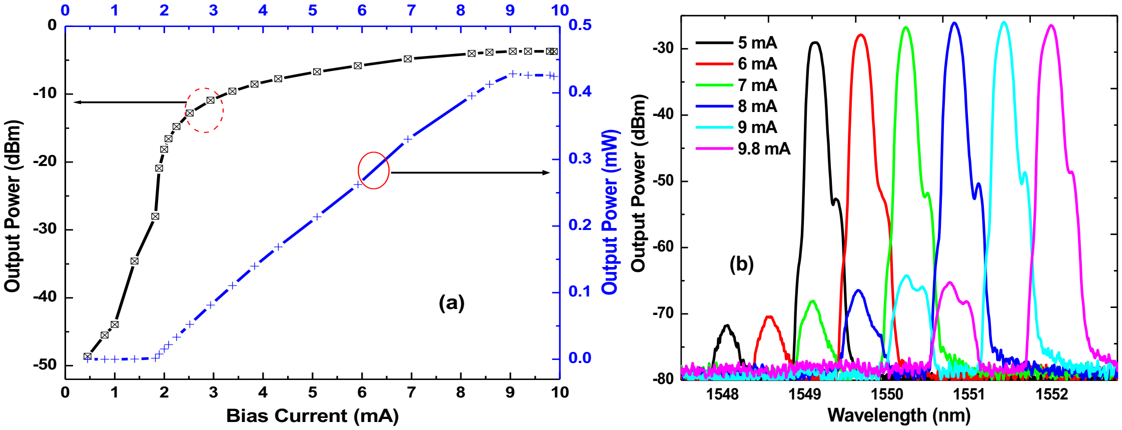

Figure 4: (a) An illustration of VCSEL biasing and (b) wavelength tuneability by increase in bias current.

The tuneability of the wavelength for VCSEL 2 is shown in figure 4 (b). The lasing threshold for VCSEL 2 from figure 4 (a) was seen to be 1.7 mA. The VCSEL can be tuned from 1547.6-1552.1 nm when a 2-9.8 mA bias current is applied. Since the best modulation and full lasing is achieved above the mid-point current (5.5 mA), VCSEL 2 was biased at 5-9.8 mA which provided a 1549.1-1552.1 nm tuneability range. This tuneability makes VCSELs ideal for wavelength conversion and WDM high speed transmission.

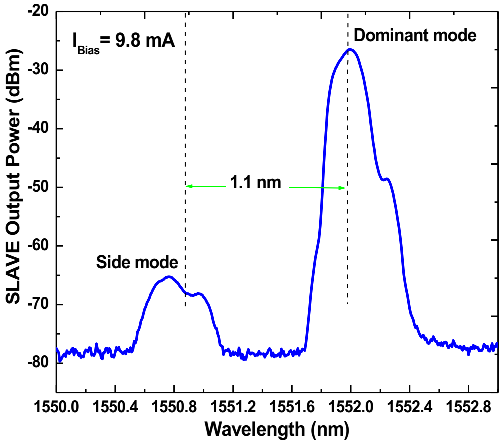

Figure 5: Shows the side- and dominant modes of a VCSEL with a 1.1 nm wavelength spacing.

The side-mode and dominant modes of VCSEL 2 are as shown in figure 5. The VCSEL was biased at 9.8 mA with a dominant wavelength of 1552.1 nm while its side-mode was at 1551.0 nm. This VCSEL had a 39 dB side-mode suppression ratio (SMSR) at 9.8 mA bias current and 1.1 nm (137.5 GHz) wavelength spacing.

To illustrate wavelength conversion, the dominant mode of VCSEL 2 was tuned to 1550.4 nm with a 1549.3 nm side-mode using a 7.6 mA bias current. As a result, to convert a 1549.3 nm signal carrier, VCSEL 2 side-mode was tuned to match the incoming wavelength. This offered an optical wavelength locked injection. The spectrum of the injected beam and dominant mode of the slave is as shown in figure 6 (a). Without optical injection, the dominant mode was a “HIGH” or logical “1” but with a 10 dBm optical injected beam, it was a “LOW” or logic “0”. This introduced data inversion when a data signal was transmitted by the master laser. The switching off of the dominant mode of VCSEL 2 with an increase in injected power is shown in figure 6 (b). The high power from the injected beam stimulated and lased the side-mode due to gain saturation. From figure 6 (b), the power of the dominant modes for different wavelengths decreased with increase in injected power. A 16 dB ER ratio of the dominant modes was obtained when a 15 dBm injection power was used for VCSEL 2 with new wavelengths 1550.4, 1550.8 and 1551.6 nm when 1549.3, 1549.7 and 1550.5 nm incoming wavelengths were converted respectively.

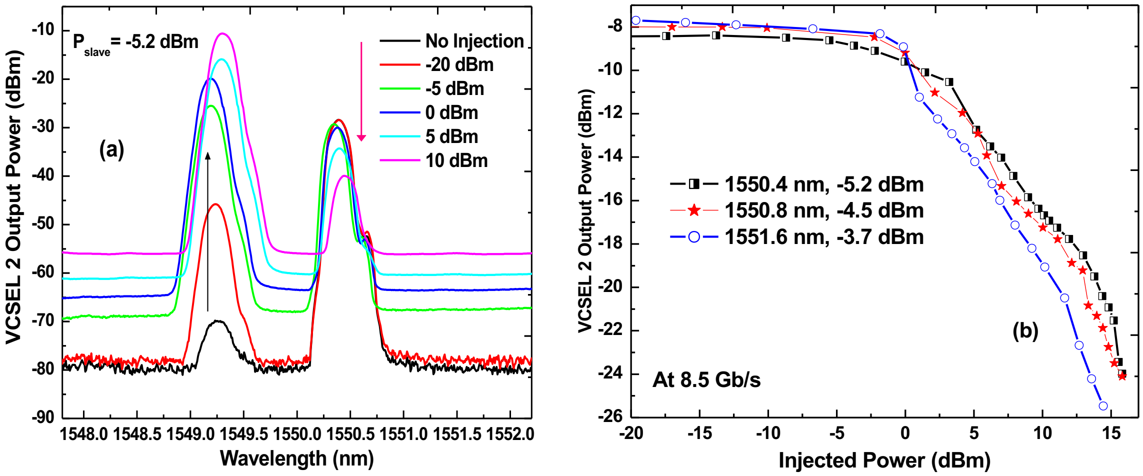

Figure 6: (a) Spectrum showing switching off of the dominant mode of VCSEL 2 and (b) extinction of dominant modes of VCSEL 2 with different new wavelengths 1550.4-1551.6 nm and increase in injection power.

The effect of wavelength conversion of an 8.5 Gb/s data signal by means of VCSEL to VCSEL optical injection, is for the first time evaluated using BER measurements at the 10^{-9} threshold level. The results are shown in figure 7. The output power for the slave was -3.7 dBm while the master laser had a -2.9 dBm output. The PIN receiver sensitivity measured for an error-free back-to-back (B2B) without conversion was -19.9 dBm. After wavelength and data conversion, the sensitivity was -18.8 dBm for a 15 dBm injection power as shown in figure 7 (a). This represented a 1.1 dB conversion penalty.

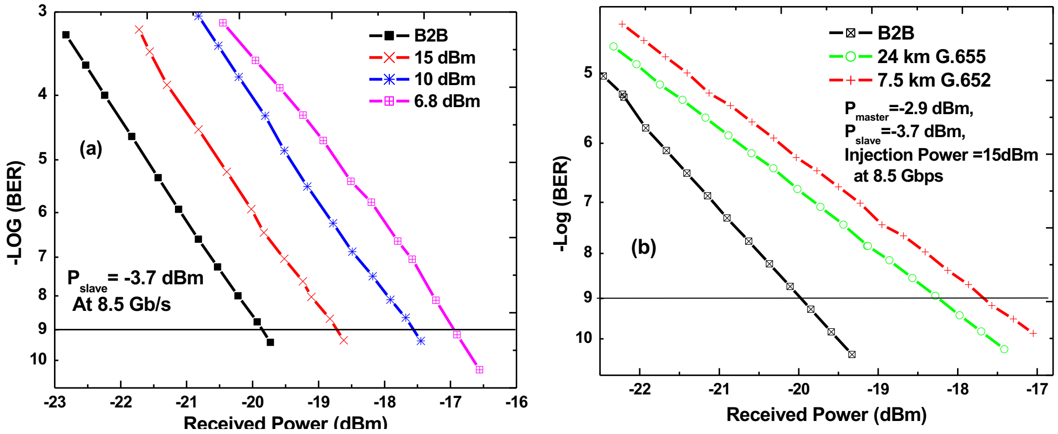

Figure 7: BER measurements for: (a) Incoming data (B2B) and converted data for varying injection powers. (b) Incoming data (B2B) and converted data and transmission over 7.5 km (G.652) and 24.7 km (G.655) fibre links.

When the converted wavelength was transmitted, a 0.5 dB transmission penalty was incurred over a 24.7 km G.655 fibre link. While over a 7.5 km G.652 fibre, a 2.3 dB transmission penalty was incurred as shown in figure 7 (b). The difference in penalties was due to the cumulative chromatic dispersion properties over the two fibres that resulted in the overlap of high speed bits during transmission.

Optical wavelength conversion based on VCSELs with an ER of 16 dB of the dominant mode of a laser cavity can be utilized in rechannelling optical WDM systems involving multiple wavelengths. Since the converted signal carrier wavelength can be transmitted over tens of kilometres of fibre, this technique can be used in complex links involving data signals. For instance, an incoming signal carrier wavelength λ_1 joining a network in which λ_1 has already been assigned to another signal leads to wavelength collision. With VCSEL-to-VCSEL wavelength conversion, the incoming λ_1 can be converted to λ_2 so that both λ_1 and λ_2 can be transmitted without collisions over a single fibre by utilizing WDM technology. Therefore, the network can be reconfigured to suit all network demands without requiring additional electrical components such as RF data signal generators.

6. CONCLUSION

A low power, purely optical VCSEL-to-VCSEL wavelength conversion with an ER of 16 dB has been experimentally achieved using a 15 dBm injection power. This has been realized at the low attenuation 1550 nm transmission window with VCSELs. The 137.5 GHz side- and dominant-mode spacing can be accommodated within an ITU flexible spectrum grid for dense-WDM transmission systems. A 1.6 dB data conversion and transmission penalty has been measured for 8.5 Gb/s data transmission over a 24.7 km fibre link. This paper demonstrates, for the first time, VCSEL-to-VCSEL wavelength conversion within the 1550 nm transmission window, including transmission over fibre and BER performance characterization. This work is vital for all optical fibre-linked applications such as access networks and WDM networks where wavelength switching is required.

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