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Application of VCSELs in next-generation telescope array networks such as the Square Kilometre array

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ABSTRACT

The distribution of precise and accurate optical clock signals across fibre links has a significant impact in various fields. Many applications require the transfer of stable and precise timing signals from a single central location to multiple remote users via a fibre network. One such application is the big data instrument, the Square Kilometre Array (SKA). An increase in demand for more bandwidth by broadband providers has prompted the expansion and development of attractive and intelligent, modern communication networks. Vertical cavity surface-emitting lasers (VCSELs) are an attractive solution and a potential candidate for realizing low cost and high bandwidth data transmission. In this paper a novel and unique, all-optical technique for measuring the one-way transmission time delay of the propagating signal along an optical fibre is presented. This has been successfully achieved by optically injecting a pulse-per-second (PPS) signal into the secondary mode of a 1550 nm VCSEL located at the client end. A round-trip latency time of 113.2 μs was experimentally measured over a 22 km G.652 single mode fibre (SMF). A novel VCSEL capacity upgrade technique is further demonstrate. This was experimentally achieved by simultaneously modulating a single 1310 nm VCSEL with a 10 Gbps $2^7 - 1$ pseudorandom binary sequence (PRBS) and a polarization based PPS clock signal. An error free transmission over 11 km of G.652 SMF was reported, with a measured transmission penalty of 0.52 dB when the VCSEL was simultaneously modulated with the $2^7 - 1$ PRBS and the polarization based PPS signal.

1. Introduction

Phase stabilization across optical fibre intended for highly stable and precise timing systems are extremely essential within astronomical telescope array and modern day communication networks. Radio astronomy has made significant progress in sensitivity and astronomical observational efficiency in recent times, with the development of next-generation radio telescopes. The SKA will be the largest and most sensitive interferometric radio astronomy instrument, split across two continents. The MeerKAT telescope will be constructed in South Africa and the Australian Square Kilometre Array Pathfinder (ASKAP) in Australia [1]. Optical fibre forms the backbone of the SKA and is needed to transmit large volumes of real time astronomical data collected from the remotely located dishes to a correlator housed at a central computing location [1–4].

Astronomical signals will be transmitted to the high performance super computer at transmission speed reaching 420 Gb/s per dish and 16 Tb/s per telescope array. Upon completion it is estimated that the SKA data rates will far exceed the data rates generated by the current internet traffic [5]. Precise time and frequency techniques over optical fibre play an important role contemporary scientific research and metrology applications. Synchronization and timing across optical fibre for telescope arrays such as the SKA, is used to establish phase coherence, low phase noise and minimal phase drift throughout the entire antenna array [1,6,7]. In linear particle accelerators, RF dissemination systems with minimum phase drift and errors are required for positrons and neutrons generation [8]. The need for intelligent transport networks for efficient data and clock tone dissemination using reliable and low cost transmitters is required.

Vertical cavity surface emitting lasers (VCSELs) are becoming the emerging optical source for modern day high-speed optical transmission and optical interconnections due to their unique attributes [9]. Due to the cylindrical design of the active region, the VCSEL emits linearly polarized light perpendicular to the active layer. It's this unique attribute that differentiates VCSELs from

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orthodox semiconductor edge emitting lasers [10,11]. VCSEL polarization dependency, stress-induced during the fabrication stages, has been comprehensively investigated over the past years [12]. Current-induced polarization switching in VCSELs has been extensively studied and established for applications demanding specific polarization orientations [13]. In this paper we report on a novel technique for measuring the round trip transmission time delays along single mode fibre. This approach is based on wavelength conversion where a 1550 nm VCSEL, located at the client end is injected with an optical pulse-per-second (PPS) clock signal into its secondary mode. The up-converted light signal is then inverted and returned to the transmitting site via an optical circulator, thereby completing the round-trip transmission link. An innovative technique of improving the carrier spectral efficiency of a single 1310 nm VCSEL is further demonstrated. This was achieved by simultaneously modulating the amplitude of the 1310 nm VCSEL with an electrical 10 Gb/s non return to zero (NRZ) PRBS of bit length $2^7 - 1$ and a linearly polarized PPS signal.

This paper is structured as follows, Sections 2 and 3 provides a brief overview on VCSELs and the wavelength conversion technique. The PPS-timing experimental procedure and the system results are presented in Sections 4 and 5. Section 6 provides a concise summary of polarization switching in VCSELs, followed by the dual modulation experimental procedure and its related results in Sections 7–9. Concluding remarks are presented in Section 10. In our previous work [14], we experimentally demonstrated the role of VCSELs in optical latency measurements. In this contribution we examined the possibility of simultaneous direct 10 Gbps data modulation and polarization-based pulse per second (PPS) timing clock signal modulation of a single VCSEL.

2. Vertical Cavity Surface Emitting Lasers (VCSELs)

VCSELs are semiconductor laser diodes consisting of a monolithic laser resonator, emitting light perpendicular to the surface of the device. VCSELs are well known for their low manufacturing cost, low threshold and drive currents. Fig. 1 illustratively shows the internal layout of a VCSEL [15]. The VCSEL inner cavity consists of a laser resonator made up of two parallel, distributed Bragg reflectors surrounded by vertically stacked electrically conductive layers. The inner cavity or active region further consists of multiple quantum wells approximately 10 nm thick [15]. Depending on the emission wavelength of the VCSEL, a number of elements are utilized for fabricating or growing the epitaxial layers. For 1550 nm optical transmission InP is the preferred substrates for epitaxial growing whereas GaAs is the substrate of choice for emission wavelengths up to 1300 nm [15,16].

3. All-optical wavelength conversion

All-optical wavelength conversion is an effective technique employed within a telecommunication network enabling efficient wavelength and optical packet switching [17]. Various wavelength conversion configurations have been studied and demonstrated, these include cross phase (XPM) and cross gain (XGM) modulation wavelength converters [17]. Another method used for obtaining wavelength conversion is by gain suppression, as illustrated in Fig. 2 [17]. An intensity modulated, incident beam λ_p from the master laser is injected into the cavity of the slave laser.

Moreover, the incident beam from the master laser, carrying the data, is injected directly into the side mode of the slave laser. During this process, the side mode is optically stimulated thereby vibrating within the gain medium [18]. Consequently, the dominant, primary mode of the tunable or slave laser is suppressed and the injected, side mode is amplified or switched on. As a result, the data carried by the injected probe wavelength is then inverted and converted to the new lasing wavelength λ_c [17–19]. Boiyo et al. [18] and Chand et al. [19] recently reported on an all-optical VCSEL to VCSEL wavelength conversion technique [18,19]. This method uses a high power incident beam to stimulate the side mode of the slave VCSEL thereby obtaining mode suppression. An extinction ratio of 16.2 dB was experimentally measured when using a 15 dBm injection power [18]. Fig. 3 illustrates the primary and secondary modes of a VCSEL before and after direct optical injection, as measured by Boiyo et al. [18].

4. PPS-timing experimental procedure

The schematic diagram of the PPS-timing system used for time delay measurements is shown in Fig. 4. A continuous wave (CW) emitted from a tunable distributed feedback (DFB) laser with a spectral width of less than 10 MHz situated at the transmission end, was injected into the secondary mode of a 1550 nm VCSEL situated at the client side, as illustrated in Fig. 4. A round trip dissemination system along the same fibre path enables the measurement of any time variations along the one-way optical link. This is based on the assumption that the transmitted signal along the two-way optical transmission link is affected by the same perturbation. The one-way latency time of the optical signal along the fibre is then determined from the experimentally measured round trip propagation time. To attain adequate gain saturation within the internal cavity of the VCSEL, a high intensity PPS signal was injected into the side mode of the slave laser source. A 1551.70 nm CW with an output optical power of 5.27 dBm from the DFB tunable laser was polarization controlled and coupled into a Mach Zehnder Modulator (MZM) biased at 2 V_{pp}. The MZM was driven by an electrical PPS signal produced by a high precision rubidium (Rb) clock with a jitter of less than 1 ns. The low jitter 5 V_{pp} PPS signal was electrically attenuated by 8 dB to 2 V_{pp} ensuring a maximized optical output from the MZM. Since the MZM is polarization sensitive, a polarization controller (PC) was used to adjust the polarization states of the injected optical signal. The injection power of the transmitted PPS optical signal was further increased by amplifying the CW tunable DFB laser source using an erbium doped fibre amplifier (EDFA), ensuring sufficient gain saturation within the lasing cavity of the VCSEL. An isolator with a 2.1 dB insertion loss was used to suppress any back reflections to the EDFA whilst a 0.3 nm full width half maximum (FWHM) tunable optical filter was positioned before the circulator to subdue noise generated from the EDFA and unwanted wavelengths introduced by the primary laser source. The optical PPS signal was subsequently transmitted along the fibre link and injected into the side mode of the VCSEL, as illustrated in Fig. 4. Wavelength conversion and inversion occurs to a new wavelength within the VCSEL as a direct result of the high-powered, intensity modulated, PPS optical signal being injection into the side mode of the secondary laser. The new converted and inverted, 1553.30 nm wavelength originating from within the lasing cavity of the VCSEL was subsequently returned to the transmitting site via the circulator and filtered using a 100 GHz channel WDM demultiplexer. Thereafter, the converted PPS optical signal was detected using a 10 GHz bandwidth positive-intrinsic-negative (PIN) photodiode with an optical sensitivity of −19 dBm and subsequently compared to a reference, electrical PPS signal generated by the stable Rb source. The time delay, $\Delta\tau$, between the rising edges of the reference PPS signal and the returned inverted beam, λc, was evaluated using an Agilent mixed signal oscilloscope. The PPS-timing experimental results are summarized and discussed in the following section.