Optics Communications 554 (2024) 130164

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Experimental demonstration of 480 Gbit/s coherent transmission using a nanosecond switching tuneable laser

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ARTICLE INFO

Keywords:
Nanosecond switching
Coherent transmission
16QAM

ABSTRACT

Fast-switching tuneable lasers with a wide wavelength coverage and with noise and linewidth levels suitable for high-order modulation formats can facilitate the implementation of highly flexible and reconfigurable optical metro, access and inter/intra data center networks. In this work, we show the characterization of a tuneable laser capable of covering a wavelength range of 35 nm in the C-band with nanosecond switching time and low linewidth and use it to demonstrate 480 Gbit/s 16QAM transmission over 25 km of single-mode fiber for a wavelength range of 19 nm.

1. Introduction

The widespread use of online services such as cloud computing, storage services and online streaming is imposing a continuous increase in the data rate requirements of optical networks. This upscaling of capacity has resulted in the transition of coherent technology from long-haul communications to ever-shorter distances. Additionally, grid flexibility and channel reconfigurability have gained importance over the last number of years [1]. In this situation, coherent technology is required to continue to deliver capacity growth in a cost-effective manner while also ensuring a high degree of reconfigurability in optical metro, access and inter/intra data center networks (through the potential introduction of optical switching technologies [2]). The key enabling technology for fast reconfigurable coherent systems is fully integrated coherent transceivers capable of high-speed optical switching [3,4].

For an optical coherent network that employs wavelength switching, low linewidth lasers providing ultrafast switching speeds in the order of nanoseconds, are required. Low power consumption and small footprint enabled by photonic integration are also key features that must be fulfilled. Previous demonstrations of widely tuneable lasers in the C-band have shown relatively large switching times [5,6], due to the need for thermal/mechanical switching [7,8], or optical 1/f frequency noise too high to support advanced modulation formats [9]. These factors could impose additional limitations on the optical transmission system. A recent publication has experimentally shown the transmission performance of a laser with nanosecond switching times, but the demonstration was limited to 100 Gbit/s quadrature phase shift keying (QPSK) for back-to-back transmission [10].

In this paper, we present the characterization of a widely tuneable, low linewidth, fast-switching laser suitable for next-generation coherent optical access and data center networks [11]. We then demonstrate its performance in continuous operation in terms of the pre-forward error correction (FEC) bit error ratio (BER) over a 19 nm wide range of wavelengths after a 25 km optical link using 480 Gbit/s dual-polarization 16-ary quadrature amplitude modulation (16QAM). This is, to the best of our knowledge, the fastest transmission rate demonstrated to date with a nanosecond tuneable laser. We find consistent performance over the whole range of wavelengths studied in this work, demonstrating the potential of the device presented for enabling optical switching of coherent signals using advanced modulation formats in future networks.

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https://doi.org/10.1016/j.optcom.2023.130164
Received 1 September 2023; Received in revised form 17 November 2023; Accepted 20 November 2023
Available online 23 November 2023
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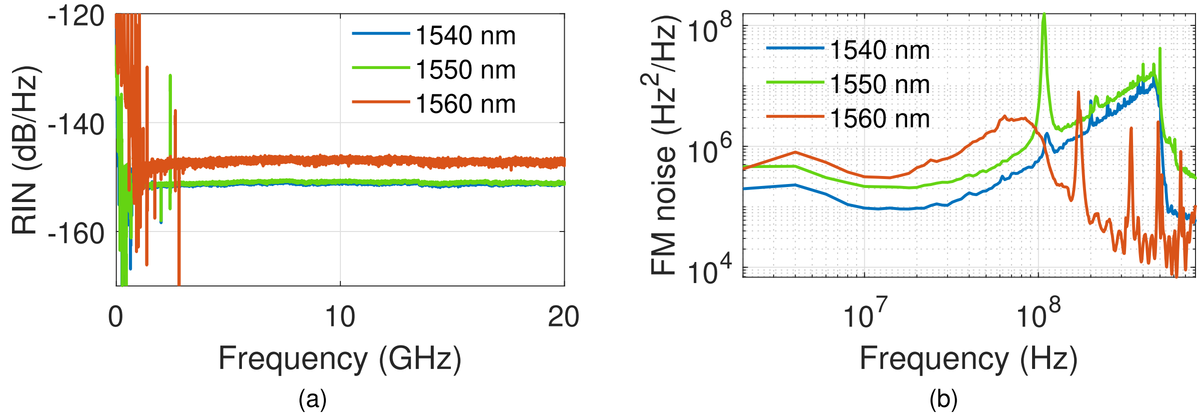

Fig. 1. (a) RIN estimation for 1540 nm, 1550 nm and 1560 nm. (b) FM noise estimation for 1540 nm, 1550 nm and 1560 nm.

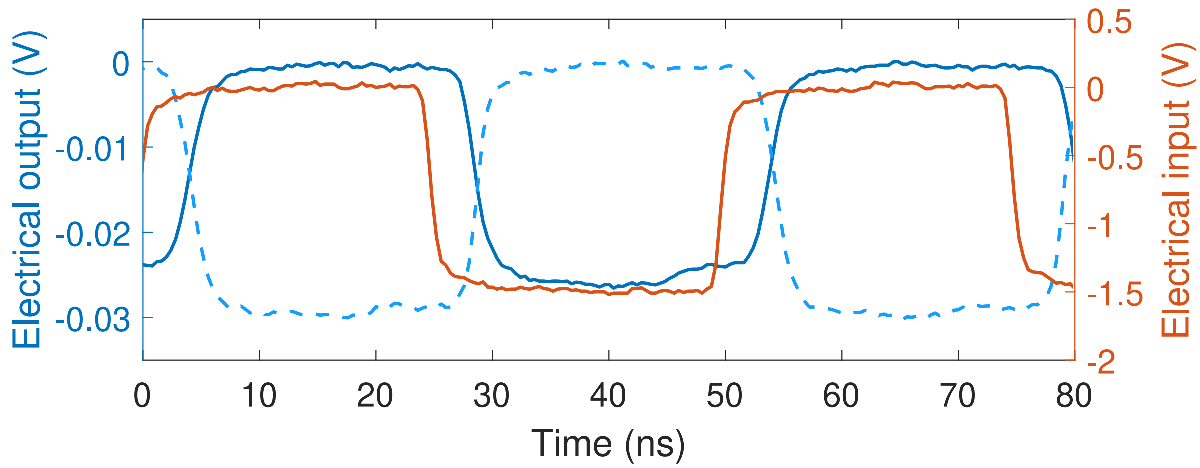

Fig. 2. Switching demonstration using 25 ns electrical pulses to tune the laser between two target wavelengths spaced by 3.5 nm. The solid and dashed blue lines show the detected optical signal obtained by sending the output of the laser through a tuneable optical filter centered at each of the switching wavelengths.

2. Device characterization

The laser structure consisted of an InGaAsP multi-quantum well gain section coupled with two tuneable ring resonators and an electro-optic phase modulator, as shown in [12]. A wavelength coverage of 20 nm was observed with a side mode suppression ratio (SMSR) of more than 50 dB when a single ring was tuned, while a total coverage of 35 nm, from 1540 nm to 1575 nm, was obtained with both rings tuned simultaneously. The device was initially characterized for three different operating points accessible by tuning a single ring resonator, corresponding to emission wavelengths of 1540 nm, 1550 nm, and 1560 nm. The relative intensity noise (RIN) was measured using the setup detailed in [13]. Values of −151 dB/Hz were obtained for 1540 nm and 1550 nm, and −147 dB/Hz for 1560 nm (Fig. 1(a)). In all cases, the measurement was thermal and shot noise limited, meaning that the actual RIN value might be lower than the figures presented here. A frequency noise measurement was performed using a delayed self-heterodyne technique explained in [14]. The frequency noise results are presented in Fig. 1(b). The curves are scaled such that the intrinsic Lorentzian linewidth can be read directly from the flat portions of the curves. For this laser, linewidth values of 100 kHz, 200 kHz, and 300 kHz were obtained at 1540 nm, 1550 nm, and 1560 nm respectively. The curves were obtained using a digital low-pass filter to remove the instability caused by optical feedback. It must be noted that the device did not have an integrated optical isolator, and recent versions of the device with an integrated isolator show linewidth values approaching the 100 kHz value over the whole operating range. Moreover, there is no evidence of deleterious 1/f frequency noise present above 1 MHz as was the case previously for fast-switching tuneable lasers based on electronic current tuning [9]. Fig. 2 shows a switching demonstration as the electrical signal to one of the ring resonators is varied to switch the laser from a wavelength of 1546.65 nm to 1550.15 nm. A switching time of around 2 ns was observed. Fig. 3(a) shows an overlapping plot of optical spectra for different tuning points, all of them showing an SMSR of over 50 dB.

3. Experimental setup

In order to demonstrate the performance of the device, a 60 GBaud dual polarization 16QAM transmission experiment was performed, resulting in a gross transmission rate of 480 Gbit/s. The experimental setup used in this work is shown in Fig. 3(b). Four pseudorandom 4-level signals 2^{16} symbols long were generated offline, filtered with a root-raised cosine (RRC) filter with a roll-off factor of 0.2, predistorted to compensate for the bandwidth limitation and the relative delays between tributaries introduced by the RF circuit of the transmitter, and uploaded into an arbitrary waveform generator (AWG) Keysight M8194 A operating at 120 GSa/s. The signals from the AWG were sent into a dual-polarization IQ modulator (IQM) with a 6 dB analog bandwidth of 40 GHz, where they modulated the four tributaries (IX,

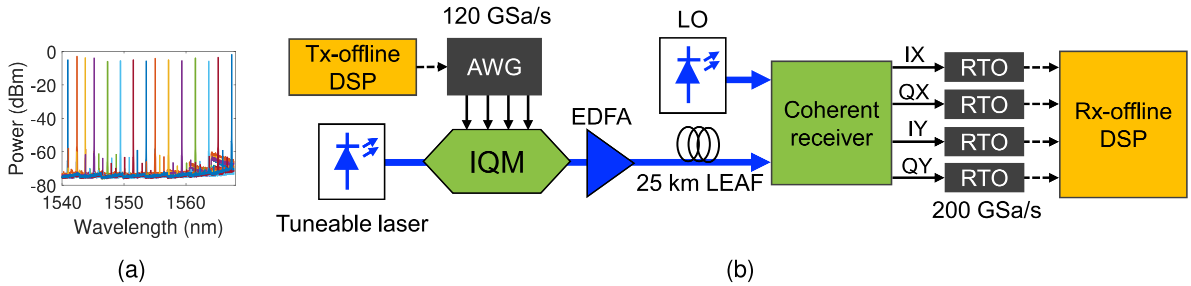

Fig. 3. (a) Overlapping spectra of several tuning points covering a 26 nm range in the C band. (b) Experimental setup.

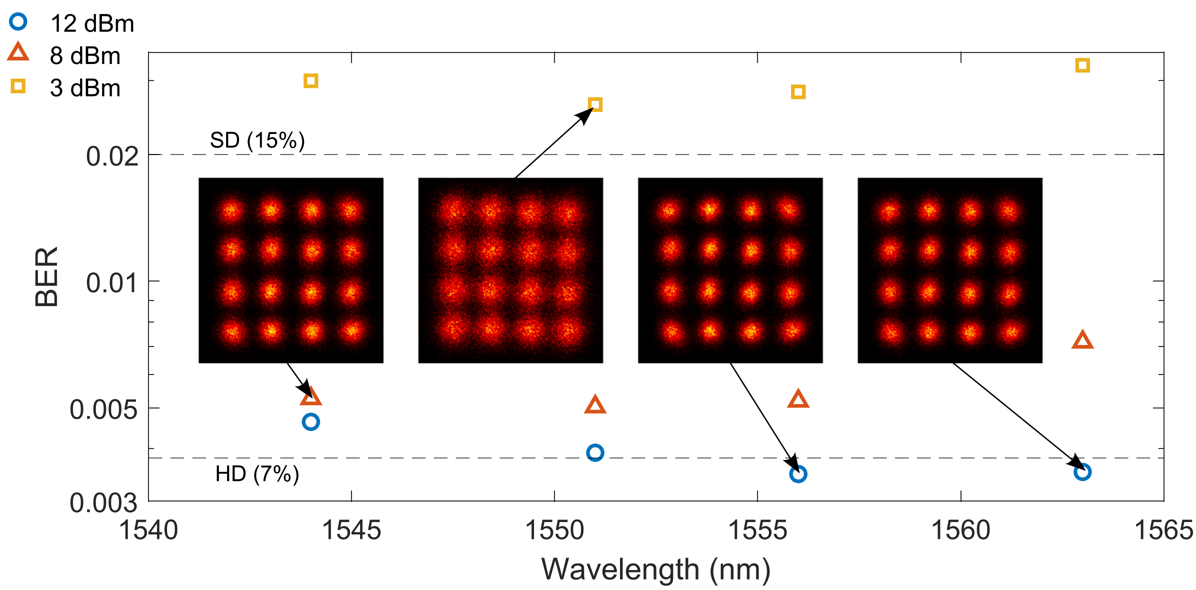

Fig. 4. BER obtained by averaging over both polarizations for different launch powers and carrier wavelengths. Dashed lines show typical values for the BER limit of a 7% overhead HD FEC and a 15% overhead SD FEC. Inset figures show the constellation diagrams of the equalized output of various operating wavelengths and launch powers.

QX, IY, QY) of the light from the laser. An external optical isolator was placed before the IQM to avoid backreflections. The wavelengths studied were 1544.1 nm, 1551 nm, 1556.6 nm and 1563 nm, accessible by tuning a single ring resonator.

After the IQM, the signal was sent to an erbium-doped fiber amplifier (EDFA) for power boosting. The total launch power over both polarizations was set to the powers of 3 dBm, 8 dBm and 12 dBm by tuning the gain of the EDFA, and the signal was transmitted over 25 km of large effective area fiber (LEAF) with a chromatic dispersion parameter of 4 ps/nm/km, attenuation coefficient of 0.19 dB/km and a nonlinear coefficient of around 0.7 1/W/km. At the receiver, an external cavity laser was used as a local oscillator (LO) and a dual polarization coherent receiver containing four balanced photodiodes (Finisar BPDV3120R) with a 3 dB bandwidth of 70 GHz converted the optical signal into electrical signals. Four real-time oscilloscopes (RTO) with a 3 dB bandwidth of 70 GHz operating at 200 GSa/s were used for capturing the electrical currents into digital signals for offline processing.

The digital signal processing (DSP) applied to the digital signals consisted of receiver skew compensation, resampling to two samples per symbol, signal normalization, IQ imbalance compensation, chromatic dispersion compensation, frequency offset compensation [15], matched filtering, and adaptive decision-directed multiple input multiple output (MIMO) equalizer. The MIMO equalizer included feed-forward equalization combined with a decision-directed carrier phase recovery for polarization demultiplexing and compensation of residual distortions. The length of the equalizer was set to 31 taps, number beyond which additional length increases do not result in noticeable performance gains. The tap weights were updated using a least means squares algorithm, and a short training sequence was used for initial convergence. The BER of the equalized signals was obtained for each of the wavelengths by averaging over both polarizations and multiple captured sequences.

4. Results and discussion

The BER results obtained in these experiments can be seen in Fig. 4. For reference, the figure shows as dashed lines the BER limit for error-free performance of a 7% overhead hard-decision (HD) FEC-coded signal and a typical BER limit for a 15% overhead soft-decision (SD) FEC-coded signal. BER values well below the SD limit can be seen both for launch powers of 8 dBm and 12 dBm over the whole wavelength range. However, the 3 dBm results are limited by a low signal-to-noise ratio (SNR) and the obtained BER values are above the SD threshold. While significant performance gains were obtained from increasing the launch power from 3 dBm to 8 dBm, only a modest improvement was observed from moving to 12 dBm. This trend can be explained by the effects of fiber nonlinearity limiting the performance at high powers and indicates that additional reductions in BER can potentially be obtained with nonlinear equalization techniques such as digital backpropagation. The obtained results were found to be consistent over the whole wavelength range, with just minor performance variations among wavelengths mainly due to differences in output power (affecting the required gain from the EDFA) and, to some extent, due to different linewidth values from the laser.

Inset figures in Fig. 4 show various constellations under different wavelengths and launch power conditions. Clear constellations can be seen for launch powers of 8 dBm and 12 dBm independently of the operating wavelength, while the constellation corresponding to a launch power of 3 dBm shows a wide spreading of the constellation points due to the degradation in SNR. From these constellation diagrams, it is clear that the laser has a low enough phase noise at all four wavelengths studied here to support 16QAM, and potentially higher-order formats.

The high SMSR, low RIN and linewidth, and low 1/f noise observed over the whole C band during the device characterization are consistent with the results presented in this section. The small variations in BER as a function of emission frequency over the wide range studied here, together with the ultra-fast nanosecond wavelength switching ensure usability and high potential for increased reconfigurability and flexibility in C band-based short-to-medium reach optical transmission systems. The BER and the constellations obtained after standard DSP were found to be consistent over the whole range of wavelengths for a given adaptation parameter on the equalizer and phase recovery algorithm. Those results were in line with the small variability of the measured values of RIN and FM noise.

5. Conclusion

We have presented the basic device characterization and system performance of a fast-switching wavelength-tuneable laser. RIN and frequency noise characterization over a range of wavelengths covering part of the C band present RIN values in the order of −150 dB/Hz and linewidths in the order of 100 kHz. We then presented the device's performance in a high-speed communication system operating at 480 Gbit/s 16QAM over a distance of 25 km, demonstrating the feasibility of using this laser for optical access, metro and data-center networks.

The nanosecond switching time, combined with the excellent performance in terms of RIN and linewidth enable this device to support high transmission rates through coherent transmission, in addition to the deployment of fast reconfigurable optical networks based solely on optical switching. The introduction of optical switching into photonic networks can avoid electronic detection and re-transmission of payload data at each node within the network resulting in lower transient times (latency) and power consumption while maintaining a small footprint.

CRediT authorship contribution statement

Marcos Troncoso-Costas: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Conceptualization, Investigation. **Gaurav Jain:** Data curation, Investigation. **Yiming Li:** Data curation, Investigation, Methodology. **Mohammed Patel:** Data curation, Investigation, Methodology. **Lakshmi Narayanan Venkatasubramani:** Data curation, Investigation. **Sean O'Duill:** Conceptualization, Data curation, Formal analysis, Investigation. **Frank Smyth:** Data curation, Investigation. **Andrew Ellis:** Funding acquisition, Methodology, Supervision, Validation, Conceptualization, Project administration. **Francisco Diaz-Otero:** Supervision, Validation. **Colm Browning:** Supervision, Validation. **Liam Barry:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by Science Foundation Ireland (SFI) through research grants 18/EPSRC/3591, 13/RC/2077-P2, 12/RC/2276-P2 and by EPSRC-SFI: Energy Efficient M Communication using Combs (EEMC) under reference number EP/S016171/1. Pilot Photonics would like to thank SMART Photonics for the collaboration around the tuneable laser development. YL thanks the Director of AiPT for funding.

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