Ultra-Fast Tunable Laser Enabling 4 ns Coherent Slot Switching Beyond 100 Gbit/s

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Abstract *We demonstrate ultra-fast wavelength switching of a narrow linewidth tunable laser. It enables coherent slot switching with a waiting time comprising laser switching, stabilization, channel estimation and data recovery under 4 ns (resp. 30 ns) for 32 Gbaud dual polarization QPSK (resp. 16QAM)*

Introduction

Dynamic time-wavelength resource allocation through optical slot switching (OSS) combined with wavelength division multiplexing (WDM) is a promising technology for data center networks. In this context, faster slot switching enables shorter time slots which increases the resource allocation granularity, resource utilization; and can reduce transmission delay[1,2]. Fast tunable lasers (FTL) are key enablers, especially with narrow optical linewidth to support coherent technologies. Several types of FTLs have been proposed such as, digital supermode distributed Bragg reflector (DS-DBR) lasers[3,4], slotted Fabry-Pérot (SFP) lasers[5,6] or switchable external cavity lasers (SECLs)[7,8]. However, designing narrow linewidth FTL spanning a large number of optical channels in few nanoseconds is a challenge. DS-DBR lasers suffer from long wavelength stabilization time after switching (>50 ns) and wide optical linewidth (~2 MHz) [4]. Compared to DS-DBR, SFP lasers exhibit superior switching and linewidth properties, but they can access fewer channels[5]. Finally, SECLs are bulky, complex to operate and suffer from a high optical frequency drift after switching due to power dissipation in different gain sections[8]. In this paper, we present a compact FTL made of a Fabry-Pérot cavity extended with one wavelength selective mirror containing two ring resonators in a Vernier configuration. We demonstrate a record laser switching, stabilization and digital signal processing convergence time for coherent OSS networks using dual polarization (DP) quadrature phase shift keying (QPSK) and DP-16 quadrature amplitude modulation (QAM) formats.

Laser design and static performances

The tunable laser sketched in Fig.1a contains a single gain section and requires only two electrical signals for wavelength tuning. It is fabricated with the III-V on silicon heterogeneous integration technology described in [9], and its small footprint (<0.2 mm²) makes it ideal for integration onto silicon-based coherent transceivers. To achieve fast wavelength switching, the selective mirror is tuned with carrier injection inside silicon ring waveguides. The measured laser spectra at a gain section bias of 150 mA and for different voltages applied on one ring resonator are plotted in Fig.1b showing that the laser can cover up to 42 nm optical bandwidth. Without injected carriers the laser signal corresponds to the shortest measured wavelength. Injecting carriers in the smallest ring shifts its resonance to the blue side

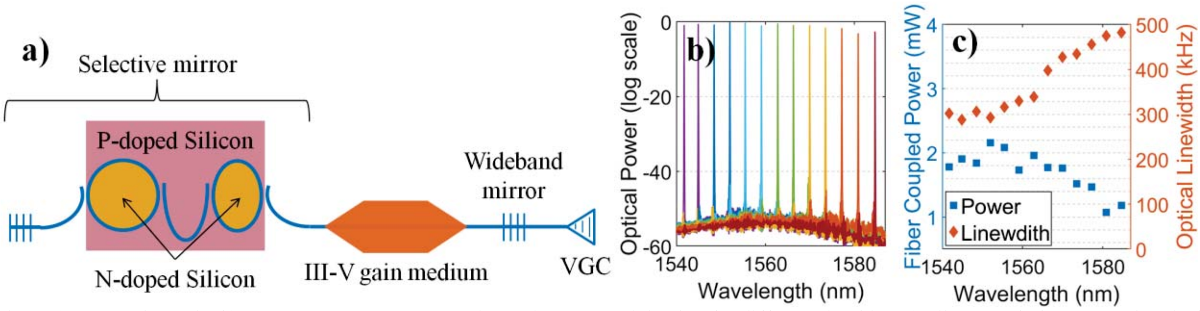

Fig.1. a) Laser schematic. b) Laser spectra at 150 mA gain section current injection for different ring bias. c) Fiber coupled power and optical linewidth across the laser optical range.

of the spectrum and by Vernier effect the laser wavelength hops to the red spectral side. Injected carriers also induce free carrier absorption, thus reducing the rings quality factor. As shown in Fig.1b, this is inconsequential on the laser side mode suppression ratio, which stays above 40 dB across the laser range. The fiber coupled laser power was measured to be >1 mW across the laser optical span (Fig.1c). The frequency dependence of the optical power in the red part of the spectrum matches the spectral response of the transmission of the vertical grating coupler (VGC) used for laser to fiber coupling. Hence, we conclude that there are no significant additional losses due to injected carriers. Fig.1c shows the laser linewidth across its optical span. With no injected carriers the laser linewidth is close to 300 kHz and increasing carrier injection widens the optical linewidth up to 490 kHz still being compliant with QPSK and 16QAM coherent systems. In the next section, we discuss the dynamic properties of the laser.

Laser response under switching

The laser switching time is measured by tuning its optical frequency every 200 ns in a round-robin manner within sets of four channels spaced by multiples of 400 GHz. The emitted wavelengths are demultiplexed and analysed on a four-channel real-time oscilloscope. Fig.2a shows the oscillograms of the power levels for one wavelength set. The laser switching time is evaluated as the time interval between power falling in one channel to power rising in the next (using 90% level threshold). The laser switching time is measured to be under 4 ns for several wavelength sets covering 21 nm in the C-band and is limited by the selective mirror driving signal falling/rising time. No relation between the laser switching time and wavelength spacing was identified. The laser switching time is then precisely studied between two channels by discriminating the laser signal power variation and optical frequency drift during wavelength tuning with a method adapted from [10] which setup is also sketched in Fig.2b. A square signal with only few picoseconds transition time is applied on one ring resonator. It switches the laser emitted frequency between two channels spaced by the second ring resonator free spectral range (~ 400 GHz). The laser signal travels through a 50 GHz optical bandpass filter (OBPF) selecting one of the two emitted wavelengths followed by a 50 GHz spacing Mach-Zehnder interferometer (MZI). The optical signal is analyzed on a sampling oscilloscope and the laser signal power and frequency drift are deduced for one channel as described in [10]. The OBPF is then tuned to the other emitted wavelength and the same protocol is repeated. Fig.2c-2d show the amplitude and frequency drift during switching. The purple and yellow curves are obtained when the OBPF is centered at ch2 and ch3, and the optical frequency drift is defined with respect to the two channels frequencies. The switching time comprising the process of laser frequency stabilization is measured to be below 1.8 ns, which is 25 times better than what has been reported with SG-DBR [4]. The claimed switching time of 500 ps in [8] might not capture the laser optical frequency stabilization time after switching and a direct comparison cannot be made. Due to the thermo-optic (TO) effect, parasitic heating generated by carrier injection in the selective mirror causes a

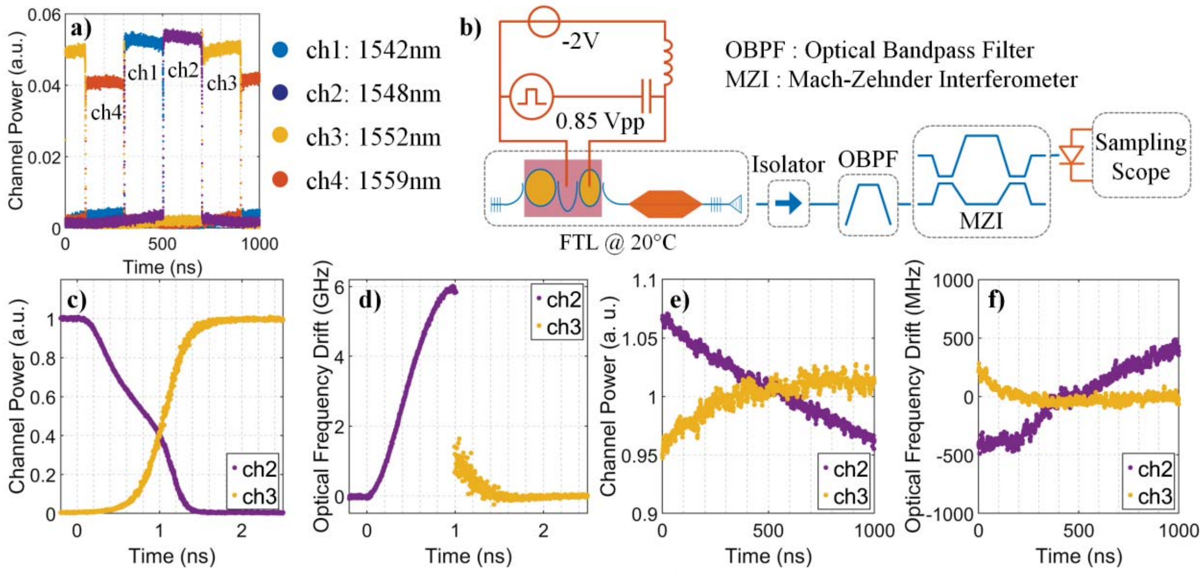

Fig. 2. a) Detected power at the oscilloscope channels. b) Experimental setup for power and optical frequency characterization in switching mode. c) & d) Power and optical frequency drift while switching. e) & f) Power and optical frequency drift in a 1µs time slot.

slow optical frequency drift, and a laser output power variation. During a 1 µs time slot and for a 400 GHz laser frequency tuning, these two variations remain under 1 GHz (Fig.2f) and 0.5 dB (Fig.2e) respectively. The required power for wavelength switching is below 5 mW for a 400 GHz frequency tuning, being an order of magnitude lower than that of SECL [7].

Coherent slot switching experiments

To assess the laser switching performances, coherent OSS experiments are performed in back-to-back. At the transmitter (Tx) the FTL switches between two wavelengths (λ) separated by ~400 GHz (ch2 and ch3 of Fig.2a). The emitted light is modulated at 32 Gbaud with DP-QPSK or DP-16QAM using a 92 GS/s digital-to-analog converter and a DP I/Q modulator. After amplification by an EDFA, the signal is sent to a coherent receiver fed by two local oscillators matching the two λ. The signal is retrieved on a 40 GS/s real-time oscilloscope and processed offline with the following steps: re-sampling at 2 samples per symbol (SPS), channel estimation (CE), down-sampling at 1 SPS, carrier frequency and phase estimation, and finally error counting. The CE is performed with constant-modulus-algorithm (CMA). Without switching, bit-error-rate (BER) versus optical signal-to-noise ratio (OSNR) is reported in Fig.3a. Only the 16-QAM exhibits a penalty with respect to additive white Gaussian noise (AWGN) theory (solid lines), measured below 1.2 dB at 7% hard-decision forward-error-correction (HD-FEC) limit. It confirms the capabilities of the proposed FTL for coherent communications. We then perform switching experiments with slot times of T_S=80 ns and 320 ns for QPSK and 16QAM leading to ~3k and ~750 recorded slots respectively. Then, two different digital signal processing (DSP) methods are used. In the first method, the CE equalizer is evaluated using only the first recorded slot for each λ. Then it is applied on all the following slots without updating it. Freezing the equalizer enables to assess the laser switching characteristics regardless of DSP adaptation performances. The corresponding counted BER along time are shown in Fig.3b-c (each point being computed by accumulating errors over all recorded slots for each λ). The transition time between slots corresponds to the time interval starting when BER goes above FEC and ending when BER returns below FEC. It is measured below 3 ns and 15 ns for QPSK and 16QAM respectively. For QPSK, it is 16 times faster than [8], and using 16QAM, we report a transition time 4.5 times faster than that reported with only single-polarization in [11]. In QPSK, no errors were counted during slots resulting in a BER below 10^{-6} being the measurement floor. In 16QAM the BER is stable, indicating that the laser frequency and phase drifts are sufficiently small to be tracked by regular DSP algorithms. In the second method, we process each slot independently to find the minimum header time T_H in which CE can be performed. Each slot is detected with a power transient at its beginning and no specific header is used for CE. We show in Fig.3d the worst BER, over all recorded slots for various T_H. We can ensure that all the slots have a BER under FEC limit with T_H ~3.5 ns for QPSK, and 30 ns for 16QAM. T_H being longer than the transition time measured freezing the DSP, a faster CE algorithm with specific headers [12] may lead to smaller T_H. For the first time to our knowledge, we demonstrate that a FTL is stable enough for performing CE in a short header time in OSS.

Conclusion

We demonstrated a wavelength switching and stabilization time of an extended cavity FTL under 2 ns. It exhibits frequency and phase stability suitable for nanosecond burst-mode coherent systems. We then demonstrate OSS experiments with a switching time comprising CE under 4 ns for 100 Gbit/s DP-QPSK, and 30 ns for 200 Gbit/s DP-16QAM.

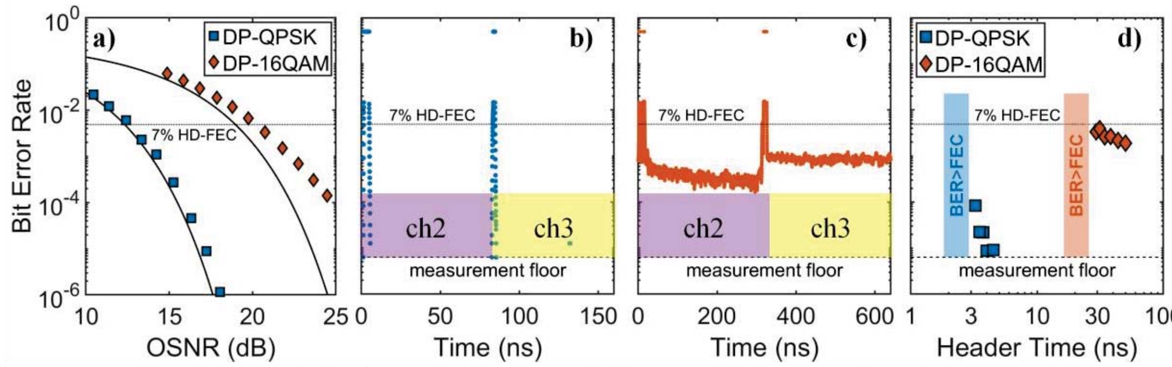

Fig. 3.a) BER vs OSNR without switching for QPSK and 16QAM, solid lines correspond to AWGN theory. b) & c) Time resolved measured BER for QPSK and 16QAM modulation format. d) Worst estimated BER among all the slots for QPSK and 16QAM for different header times.

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