Subnanosecond Wavelength-Tunable Heterodyne Receiver and Analysis of Its Fundamental Switching Speed

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***Abstract*—We experimentally demonstrate subnanosecond tunability of a heterodyne receiver employing a fast-switching local laser oscillator. A <0.7-ns switching time and the feasibility to achieve hitless switching are demonstrated. Theoretical analysis of the transition process indicates that switching time shorter than a single bit slot can be realized in a typical receiver configuration with a fast-switching local oscillator.**

***Index Terms*—Optical communication, optical receivers, optoelectronic devices, tunable receiver.**

I. INTRODUCTION

WAVELENGTH-TUNABLE transmitters and receivers are two approaches to achieving multiple access in wavelength-division-multiplexed (WDM) networks. They provide greater flexibility in dynamic networks and better utilization of resources compared to static systems. In packet-switched networks, ultrafast tunable components are desired to realize instantaneous channel selection on a per-packet basis. Recently, fast-tunable transmitters have been widely studied and significant progress has been made [1], [2]. In [1], a wavelength switching time of 0.8 ns among different channels was achieved. Although ultrafast receivers can provide similar access capability in dynamic optical networks, they have been less reported to date. In the past, most tunable receivers were based on tunable filters [3] or photodetector arrays combined with arrayed-waveguide gratings (AWGs) [4], which operate with a switching time on the order of ten nanoseconds. A new tunable receiver based on a tunable metal–semiconductor–metal (MSM) device was recently reported with a switching time of ~1 ns [5], however, within a narrow tuning range of ~70 GHz.

Coherent receivers employing fast-switching local oscillators are candidates for tunable receivers due to their wide tunability, potentially ultrafast switching capability, and good channel selectivity. Recently, a heterodyne receiver was demonstrated with an estimated 4-ns switching time [6], however, without showing the transition process. To date, a tunable receiver with less than 1-ns switching time has not been reported. In this letter, we demonstrate an ultrafast tunable heterodyne receiver showing a <0.7-ns switching time. The tuning process is fast enough to enable hitless switching [7] in a 1.25-Gb/s system, provided that the switching occurs at the transition of two neighboring bits. To the best of our knowledge, this is the fastest tunable receiver demonstrated to date. Furthermore, we perform an analytical investigation combined with experimental verifications to characterize the receiver and understand the transient process in switching. Our study reveals that the fundamental switching speed is limited by the bandwidth of the intermediate frequency (IF) filter of the heterodyne receiver, which would ensure bit-level switching if the filter is properly designed.

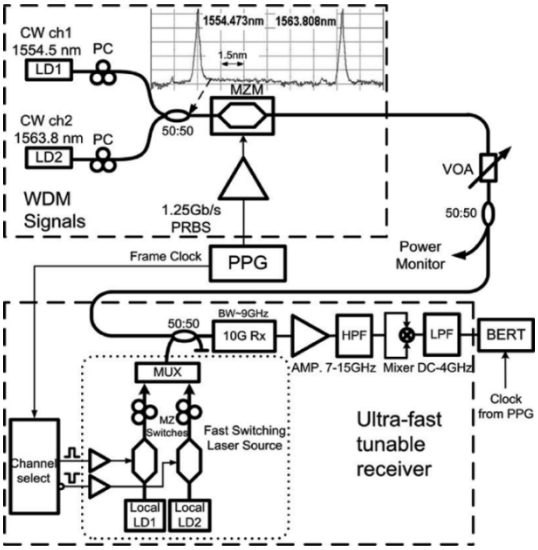

Fig. 1. Configuration of tunable heterodyne receiver and experimental setup.

II. EXPERIMENTAL SETUP AND RESULTS

The configuration of the ultrafast tunable heterodyne receiver is shown in Fig. 1. It mainly consists of a fast-switching laser source (dotted block) as the wavelength-tunable local oscillator (LO), optical mixing and reception, and a square-law detection component with IF channel selection for signal demodulation. The fast-switching LO contains a laser array and a group of on–off switched Mach–Zehnder (MZ) modulators, which are controlled in such a way that only one channel can be switched on at a time. In practice, an array of electroabsorption modulated lasers (EMLs), or an ultrafast tunable laser as described in [1],

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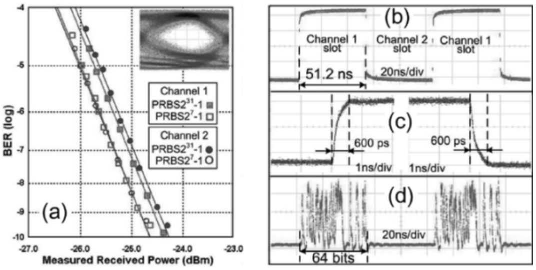

Fig. 2. (a) Measured BER performance of two channels in continuous operation mode with inset eye diagram. (b) Electrical switching-control signal. (c) Zoom-in picture of LO optical switching signal. (d) Demodulated bit stream of single channel.

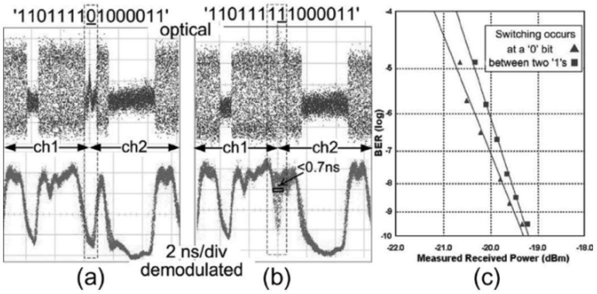

Fig. 3. Measured waveforms showing transient effects of different data patterns: (a) switching at "0" bit and (b) between two "1"s. (c) BER performance for two cases.

can be used for this purpose. Our scheme ensures ultrafast frequency stabilization of the LO during the switching transition. At the output of the MZ switches, polarization controllers (PCs) are used to align the polarization state of the LO with that of the input signal. After passing a WDM multiplexer, the LO is mixed with the signal light in a 3-dB optical coupler. The resulting optical signal is detected by a 10-G optical detector and then amplified before being launched into a high-pass electric filter (HPF), which selects the ~8.4-GHz IF component carrying the data. The IF signal is converted by a square-law mixer and then sent through a low-pass filter (LPF) to recover the baseband data, which is then delivered to the bit-error rate tester (BERT) for BER measurement.

A fast channel-access experiment employing two wavelengths is performed to investigate the performance of the tunable heterodyne receiver, as illustrated in Fig. 1. The wavelengths of the two continuous wave (CW) signals are 1554.473 (channel 1) and 1563.808 nm (channel 2), respectively, and their spectra after a 3-dB coupler are shown in the inset of Fig. 1. The channel spacing can be much smaller, which is only limited by the IF requirement. An MZ modulator is used to generate 1.25-Gb/s nonreturn-to-zero (NRZ) data. The LO output power is controlled to be ~ -2 dBm to avoid saturation in the 10-G detector. The LO wavelength can be switched between 1554.540 and 1563.875 nm, which are 8.4 GHz away from the signal wavelengths to be selected, respectively, in order to suppress noise and minimize possible intersymbol interference. The tolerance to wavelength drift in a heterodyne system is usually dependent on the bandwidth of the IF filter. In the experiment, the IF bandwidth is ~2.5 GHz and wavelength stability of the lasers is within ±100 MHz/h. In practical systems, frequency stabilization or a tracking mechanism can be used to further enhance the performance.

We first perform a BER measurement in continuous operation mode to show the tunability of the receiver. The BER results with 1.25-Gb/s NRZ signals are shown in Fig. 2(a). The measured sensitivities are -24.5 for channel 1 and -24.4 dBm for channel 2. Very small pattern dependence is observed for pattern lengths of $2^7 - 1$ and $2^{31} - 1$. The sensitivities could be further improved by using electric filters with better response and an optical receiver with higher saturation power level allowing the use of a high-power LO. We then study the ultrafast tunability of the receiver when it is set in switching mode. Two complementary electrical switching control signals are obtained from the frame output of the pulse pattern generator (PPG) to drive two MZ optical switches that gate the CW outputs from two DFB lasers. One signal is shown in Fig. 2(b) with slot duration of 51.2 ns. The LO source then switches between the two channels periodically and selects the desired channel accordingly. Fig. 2(c) provides the measured output of the switching LO when only one LO channel is turned on, which shows the rising and falling edges of less than 600 ps. To ease switching control and to obtain synchronization from the frame output port of the PPG, the pattern length is set to 128 in the DATA mode by employing a pseudo-random bit sequence (PRBS) of $2^7 - 1$ with an extra "1" bit, and switching occurs every 64 bits. Here, two channels are used to show the switching characteristics; however, similar results can be expected in multichannel systems. The capacity of the receiver can be extended by using an integrated multichannel EML or tunable laser as the LO source.

Fig. 2(d) shows the recovered bit stream when only one data channel is turned on, which clearly demonstrates the channel-selection function as the LO switches between different wavelengths. In Fig. 3, we provide the waveforms near the switching transients under the two-channel input condition for two cases: switching occurs at a "0" bit [Fig. 3(a)] and between two neighboring "1" bits [Fig. 3(b)]. The optically-mixed signal after the 3-dB coupler and the electrical bit stream at the receiver output are shown to illustrate the data recovery process. The BER curves for the two switching cases are plotted in Fig. 3(c). The sensitivities are -19.5 dBm for the "0" bit case and -19.3 dBm for the "1" bit case, respectively. Error-free operation can be achieved, although with a relatively large penalty of ~5 dB. The penalty is primarily attributed to the finite extinction ratio of the MZ modulators in the switching mode, which results in the residual light of the OFF channel generating IF interference. It is worth noting that the switching between two neighboring "1"s results in almost the same penalty as in the "0" bit case, implying that the switching transient is not a limiting factor in the demonstration. Fig. 3(b) provides a clear view of the switching process, which is less than 0.7 ns. This indicates the switching speed is related to the LO transition with a switching time of 0.6 ns. The tunable receiver is fast enough to enable hitless switching in this 1.25-Gb/s system.

In this experiment, the bit streams of two channels are kept in phase to ensure the BER measurement, while in the cases of random phases between two packets a fast clock-phase recovery should be employed for correct data reception. In addition, a practical system can use polarization diversity technology to solve the problem of random polarization states of

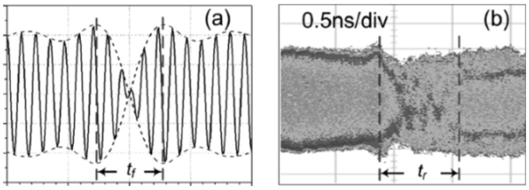

Fig. 4. (a) Simulated electrical IF signal after IF filtering and (b) measured result after HPF in switching transition.

incoming signals. Better sensitivity can be expected by using a balanced detection receiver and further optimizing the central frequency and the bandwidth of the IF filter to maximally reduce the interference and noise.

In this particular experimental demonstration, the data patterns of the two channels originate from the same source, which would correspond to the scenario where a backup channel is quickly selected without downtime when the primary path in the network breaks down, or so-called "hitless" switching [7]. To trigger fast switching, a high-speed failure monitoring and switching control module should be employed in practical systems. This hitless protection-switching scheme using the heterodyne receiver shows potentially high sensitivity through coherent detection, which is beneficial for short-reach links [8].

III. ANALYSIS OF TRANSITION PROCESS

We have shown that the switching time is <0.7 ns, while the LO transition takes 0.6 ns. It is worth noting that the switching time can be further reduced by using faster MZMs and driver electronics. Furthermore, the ultimate switching time is limited by the IF filter bandwidth as studied in this section.

Assuming an ideal LO switching source with a rectangular waveform and parallel orientation of the signal and the LO, the received IF signal in the switching transition can be written as

$$I_{\mathrm{IF}}(t) \propto A_{\mathrm{IF}} \{\cos(\omega_{\mathrm{IF}} t + \varphi_1) u(t) \\ + \cos(\omega_{\mathrm{IF}} t + \varphi_2)(1 - u(t))\} \quad (1)$$

where ω_{IF} is the intermediate frequency with an assumption that the two channels possess the same IFs. $u(t)$ is the unit step function, and A_{IF} is the amplitude of the IF signal assuming that the two channels have the same signal and LO optical powers. The integers denote the corresponding channel. φ_1 and φ_2 are the random phases of IF components of the two channels. The phase jump occurring at the switching transient contains abundant high-frequency components, while a real receiver system is bandwidth limited. The frequency response of the equivalent IF filter can be modeled as a rectangular function centered at the IF of ω_{IF} with a bandwidth of $B_{\mathrm{IF}} = \omega_f / 2\pi$. Using Fourier transform analysis, the corresponding waveform of the resulting IF signal through the filter can be written as

$$I_{\mathrm{IF}}(t) \propto \left(\frac{2A_{\mathrm{IF}}}{\pi}\right) Si\left(\frac{\omega_f t}{2}\right) \sin\left(\omega_{\mathrm{IF}} t + \frac{\varphi_1 + \varphi_2}{2}\right) \\ \times \sin\left(\frac{\varphi_2 - \varphi_1}{2}\right) + A_{\mathrm{IF}} \cos\left(\omega_{\mathrm{IF}} t + \frac{\varphi_1 + \varphi_2}{2}\right) \\ \times \cos\left(\frac{\varphi_1 - \varphi_2}{2}\right) \quad (2)$$

where the sine integration function is $Si(\omega_f t/2) = \int_0^{\omega_f t/2} \sin x / x dx$. The function $Si(\omega_f t/2)$ exhibits a finite switching time of $t_f = 2\pi \cdot 2/\omega_f = 2/B_{\mathrm{IF}}$, which is determined by the IF filter bandwidth B_{IF}. Fig. 4(a) illustrates the result of (2) in the worst case of phase jump, i.e., $\varphi_1 = 0$ and $\varphi_2 = \pi$. The dashed line indicates the envelope function $Si(\omega_f t/2)$ through the transition of the IF signal with a duration of t_f. Fig. 4(b) provides the measured electric IF signal after the HPF when the oscilloscope is set in color grade mode, showing the superimposed waveforms for all possible phases. The experimental result demonstrates a similar structure of the waveform in transition as in the simulation, and a <0.7-ns transition time t_r can be clearly observed. Note that the switching transition of the waveform in the experiment also contains the effects of finite LO-switching time, which is 0.6 ns.

The above analysis shows that the switching speed is ultimately limited by the finite IF bandwidth of the receiver system. Our analysis is independent of the data rate; therefore, the result, in general, applies to switching systems using heterodyne detection receivers. Typically, in such receivers, the IF bandwidth is wider than the data-signal spectrum; therefore, switching within a bit slot can still be maintained in higher data-rate systems.

IV. CONCLUSION

We have demonstrated an ultrafast tunable heterodyne receiver using a fast switching laser source as the LO. A <0.7-ns switching time was obtained, which is the fastest to date, to the best of our knowledge. Error-free operation during the switching process can be achieved to ensure hitless switching. The switching time of the receiver is limited by finite LO switching speed and IF filtering bandwidth. Our theoretical study reveals that a typical heterodyne receiver with fast LO can realize switching within a single bit slot.

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