Dynamically Tunable Lasers Phase NoiseCharacterization and their Use in a 10 Gbps Optical Coherent Transmission System

Dynamically Tunable Laser Phase Noise Characterization and Use in a 10-Gb/s Optical Coherent Transmission System

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***Abstract*—Commercial dynamically tunable lasers (DTLs) for dense wavelength-division-multiplexing optical networks are integrated devices into a butterfly package. Thus, their dimensions are much smaller than standard external cavity tunable lasers. Despite the reduced size, they present unexpected low phase noise. In this letter, the DTL phase noise is fully characterized for real-time optical coherent communication applications by using a suitable measurement technique based on an optical phase-locked loop. We experimentally demonstrate that DTLs can be used in a 10-Gb/s binary phase-shift-keying coherent optical communication system based on a phase-locking technique and a decision-driven architecture.**

***Index Terms*—Homodyne detection, optical phase-locked loops (OPLLs), phase noise, phase-shift keying.**

I. Introduction

COHERENT detection systems have always been attractive due to their performance advantages over direct detection systems. Even if digital signal processing (DSP) could reduce the effect of the phase noise on the system performance [1], the laser linewidth is still one of the most important factors that limits coherent detection performance. For this reason, the laser used in coherent optical transmission systems should have excellent characteristics in terms of wavelength stability and narrow linewidth.

Therefore, as shown by Norimatsu *et al.* [2], when using standard distributed feedback lasers with 10-MHz typical linewidth, the loop delay introduces a very large penalty, which will completely disable the system. For this reason, most of the experiments on coherent optical transmission systems, without DSP at the receiver, need high-performance external cavity tunable lasers with a very narrow linewidth and large physical dimensions, generally used for laboratory purposes.

In the following, we demonstrate that dynamically tunable lasers (DTLs) (devices with a reduced physical size due to their butterfly package, and commercially available for optical network systems) present a low phase noise and they can be used in coherent optical communications. In order to evaluate the DTL performance, we realized a 10-Gb/s binary phase-shift keying (BPSK) homodyne transmission, based on a subcarrier-optical phase-locked loop (SC-OPLL) coherent receiver [3]. An optical interferometer was introduced into the receiver in order to filter out the spurious spectral components at the optical local oscillator (LO) output. This system worked in real time without using digital signal processing. However, this type of laser can also be employed in optical communications where coherent detection is based on digital signal processing as well.

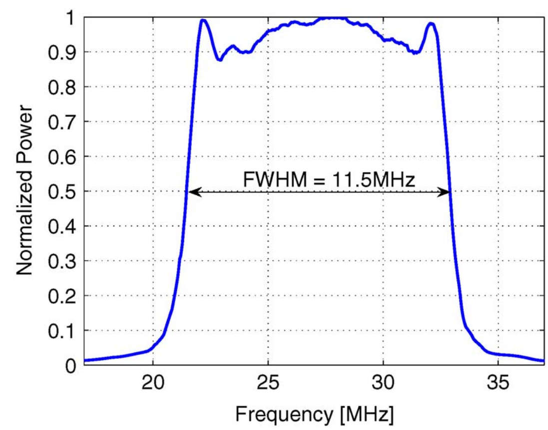

Fig. 1. Delayed self-heterodyne measurement result for Pirelli DTL taken by an electrical spectrum analyzer with 300-kHz resolution bandwidth. Measured linewidth is Δv = full-width at half-maximum/2 $= 5.75$ MHz.

II. Phase Noise Characterization

DTLs' phase noise was characterized by means of two different techniques: the delayed self-heterodyne [4] and the optical phase-locked loop (OPLL) [5]. The first measurement setup included a 620-m spool of fiber as delay line and an acoustooptic modulator with a 27-MHz frequency shift. Fig. 1 shows the spectrum detected by an electrical spectrum analyzer having a 300-kHz resolution bandwidth; it shows a linewidth of 5.75 MHz.

The second characterization was carried out by adopting the measurement technique described in [5], using two DTLs. These DTLs are commercial devices in butterfly package, specially developed for optical network systems and supplied by Pirelli. The OPLL used for the phase noise measurement is an SC-OPLL [3]. The signal power at the photodiode input was

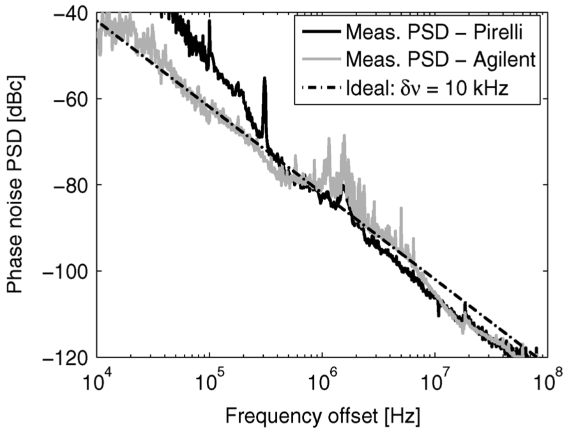

Fig. 2. Measured phase noise PSD of Pirelli DTL and Agilent 81640A. A theoretical PSD with a linewidth of 10 kHz is superimposed.

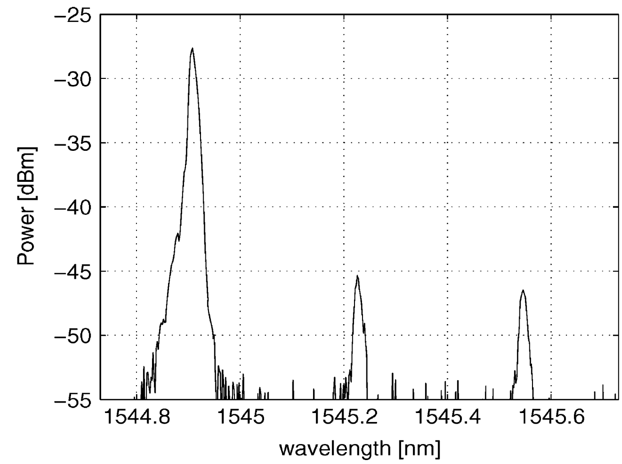

Fig. 3. LO power spectrum measured at the 90° hybrid PM input without ASE noise (resolution bandwidth $= 0.01$ nm).

set to -16 dBm, while the overall LO power was -3 dBm. The photodiode has a responsivity equal to 800 V/W. The optical voltage controlled oscillator (VCO) includes a 10-GHz $LiNbO_3$ intensity modulator and a 6-GHz electrical VCO. The loop filter is a first-order active filter, whose time constants are $\tau_1 = 1$ μs and $\tau_2 = 0.22$ μs. These time constants were chosen in order to obtain a second-order OPLL transfer function with natural frequency $f_n = 1$ MHz and a damping factor $\zeta = 0.707$.

Fig. 2 shows the measured phase noise of the DTLs power spectral density (PSD). The same characterization was repeated for Agilent 81640A laboratory lasers (an additional measured curve is shown in Fig. 2). An ideal phase noise PSD is also plotted in Fig. 2, and it is obtained by considering the combination of two identical white frequency noises with 10-kHz linewidth.

Even if the delayed self-heterodyne measurement returned a large 5.75-MHz linewidth, the phase noise PSD of the DTLs is equivalent to Agilent for frequencies over 400-kHz approximately, which is the frequency range of interest for optical coherent communications. The phase noise at lower frequencies is significantly filtered out by the OPLL transfer function [2]. This phase noise contribution can be considered negligible and, therefore, the amount of phase error introduced by the DTLs, in coherent communications, is comparable with the phase noise generated by an ideal laser with white frequency noise of 10-kHz linewidth, as shown in Fig. 2.

The large linewidth measured at frequencies lower than 400 kHz, shown in Fig. 2, is the result of the lasers' control circuits that generate spurious tones at frequencies that are a multiple of 100 kHz. Furthermore, the DTLs' phase noise PSD curve deviates from the ideal white frequency noise curve, and it is steeper at low frequencies. The linewidth, measured by the delayed self-heterodyne technique, is consequently larger [5], due to the fact that a slow frequency deviation can be considered as a drifting of the Lorentzian spectrum in time domain. In the self-heterodyne measurement technique, this drift contributes to increasing the measured linewidth. In coherent optical systems, such a slow drift is tracked and then compensated by the OPLL locking operations. Therefore, it does not affect overall performance [5].

III. 10-Gb/s BPSK Transmission System

In order to evaluate the DTL's performance by means of an optical coherent system, we have implemented a 10-Gb/s BPSK homodyne receiver based on a decision-driven architecture and an SC-OPLL [6]. The most important SC-OPLL element is the optical VCO (OVCO). This element is composed of an electrical VCO that generates a sinusoidal signal at frequency f_{VCO}. This signal is used to modulate the optical signal, through a Mach–Zehnder modulator, at frequency f_{LO}, generated by the DTL laser. The OVCO output spectrum is composed of one residual spectrum line at frequency f_{LO} and two subcarriers generated by the modulation at frequencies $f_{\mathrm{LO}} \pm f_{\mathrm{VCO}}$. One of the two subcarriers is used as the LO signal to lock the received signal phase variation. In this experiment, we introduced a Michelson interferometer at the OVCO output, in order to filter out the spurious unused subcarrier, obtaining the LO optical power spectrum shown in Fig. 3.

In wavelength-division-multiplexing (WDM) and ultra-dense-WDM transmission system applications, it is fundamental to use, at the coherent receiver, an LO without spurious spectral components. The LO spectrum needs only one spectral line to be included, in order to avoid interference in the kth channel demodulation, due to the beating between the spurious LO spectral component (the unused subcarrier) and other WDM channels. The experimental system setup is shown in Fig. 4.

The transmitter is based on a $LiNbO_3$ phase modulator, driven by an electrical nonreturn-to-zero 10-Gb/s pseudo-random binary sequence (PRBS), whose amplitude was set equal to the modulator $V_\pi = 5$ V. The source laser is a Pirelli DTL1510460, and the emission wavelength was set up to 1544.926 nm. We added a variable amount of amplified spontaneous emission (ASE) noise at the transmitter. Thus, the performance of our system is evaluated through bit-error-rate (BER) measurements versus the optical signal-to-noise ratio (OSNR) at the receiver side. An optical filter with a 0.4-nm bandwidth is used, in order to reduce the ASE noise.

The coherent receiver is based on an optical 90° hybrid; the optical signals at the two hybrid output ports, in-phase (I-ARM)

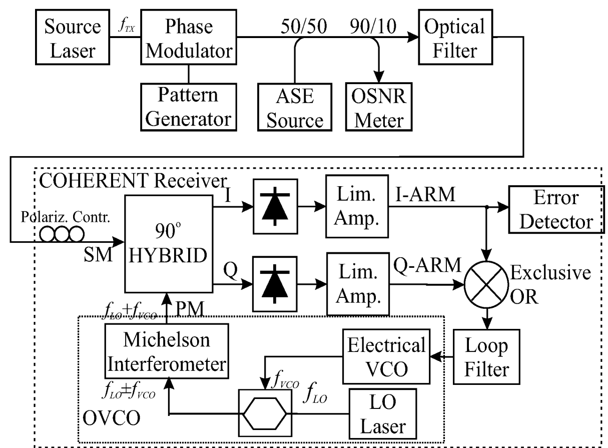

Fig. 4. BPSK experimental setup.

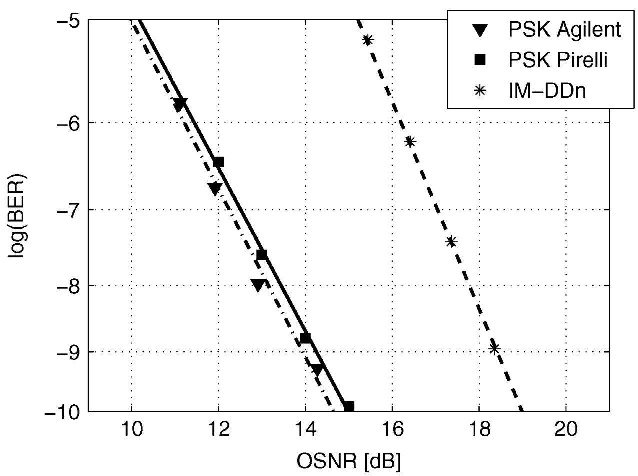

Fig. 5. Measured BER versus OSNR (0.1-nm resolution bandwidth) of 10-Gb/s PSK and IM-DD systems (PRBS: $2^{31}-1$).

and in quadrature (Q-ARM), are converted into the electrical domain by means of two amplified photodiodes with a responsivity of 300 V/W and 11-GHz electrical bandwidth. The adopted configuration keeps the received signal power constant to −16 dBm, at the I and Q photodetectors input. The two I and Q photodetectors output signals are squared and multiplied by an exclusive OR (XOR). The resulting voltage is processed by the loop filter, configured with $\tau_1 = 314.84$ ns and $\tau_2 = 74.8$ ns. The output signal tunes the frequency of a 40-GHz electrical VCO. The LO laser is a Pirelli DTL1510460, and the emission wavelength was set up to 1545.244 nm. The optical signal is modulated by an Avanex 40-GHz $LiNbO_3$ amplitude modulator, driven by the electrical VCO output. The Michelson interferometer is used to filter out the spurious unused subcarrier spectral component. The spectrum, measured with a resolution bandwidth of 0.01 nm at the 90° hybrid polarization-maintaining (PM) input, is shown in Fig. 3. The LO signal, measured at the I and Q photodiodes input, was −13 dBm. Fig. 5 shows the measurement results.

The same experiment was performed again, and the two Pirelli DTLs were replaced with two Agilent 81640A, which are external cavity tunable lasers for laboratory purposes. In this experiment, we also removed the Michelson interferometer and the LO signal was set to the same power for each subcarrier spectral component. The measurement results obtained with Agilent lasers are shown in Fig. 5: with respect to the experiment performed with Pirelli lasers, it is worth noticing that there is a penalty lower than 0.5 dB, which can be correlated to a nonoptimal receiver setup. This result, in accordance with the previous measurements, confirms that commercial DTLs, used in coherent systems, return the same performance as laboratory lasers.

Furthermore, it was experimentally verified that the spurious tones at frequency multiples of 100 kHz, generated by the lasers control circuit, do not introduce any performance penalty.

We also demonstrated that the introduction of a Michelson interferometer, used to filter out the spurious unused subcarrier, does not introduce penalty in the system performance.

In order to test an equivalent intensity modulation direct detection (IM-DD) system, we used the same noise loading configuration, optical filter, photodiode, and limiting amplifier. Fig. 5 also shows the IM-DD measurement results: coherent detection performs approximately 4.5 dB better than direct detection at a BER $= 10^{-9}$.

IV. Conclusion

The proposed measurement and experimental results show that commercially available Pirelli DTLs, in a butterfly package, have an unexpected good phase noise performance from the coherent optical communications point of view. Such an important result is a further step towards a future implementation of real-time coherent detection in optical communication systems. Furthermore, we have demonstrated that it is possible to filter out the spurious unused subcarrier in the SC-OPLL LO signal without any penalty.

Acknowledgment

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