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Impact of Mechanical Vibrations on Laser Stability and Carrier Phase Estimation in Coherent Receivers

Maxim Kuschnerov, *Student Member, IEEE*, Kittipong Piyawanno, Mohammad S. Alfiad, *Student Member, IEEE*,
Bernhard Spinnler, Antonio Napoli, and Berthold Lankl, *Member, IEEE*

***Abstract*—Coherent communication systems are largely limited by the laser linewidth of the local oscillator. In addition to phase noise, large frequency deviations can occur if the laser is mechanically vibrated. The detrimental effect of the frequency instability is measured for coherent optical receivers on a typical laser and numerically analyzed for quadrature phase-shift keying and 16-quadrature amplitude modulation using common feed-forward carrier phase recovery algorithms.**

***Index Terms*—Carrier phase estimation, coherent systems, laser, local oscillator, vibration.**

I. INTRODUCTION

COHERENT receivers are the key technology for future fiber-optic systems with transmission rates of 100 Gb/s per wavelength and above. Dominant channel effects like chromatic dispersion (CD) and polarization-mode dispersion (PMD) can be fully compensated using linear filtering, thus increasing link tolerances compared to incoherent systems. In the receiver, the optical field is mixed down to the electrical domain with a local oscillator. The phase of the transmitter and receiver oscillators is not fully synchronized, leading to a carrier phase and frequency offset that has to be compensated using digital signal processing [1]–[3].

Most research experiments for future coherent systems use offline signal processing on a computer with only limited real-time experiments being published. This makes it impossible to observe transient effects such as polarization rotations [4]. Another important transient impairment is the frequency instability of the local oscillator that can be observed in the presence of mechanical vibrations and has been extensively covered for other communication systems [5]–[7]. However, the stability of typical lasers used in fiber communications has not been commented upon yet. In this contribution, the frequency stability of a typical external cavity laser (ECL) with a linewidth of 100 kHz is tested in the presence of mechanical vibrations. The implications for coherent receivers are analyzed for quadrature phase-shift keying (QPSK) and 16-quadrature amplitude modulation (QAM) formats using common feed-forward carrier phase recovery algorithms.

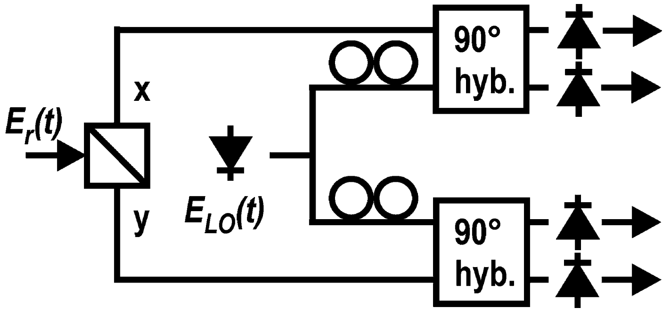

Fig. 1. Coherent optical polarization diversity receiver used in the measurements.

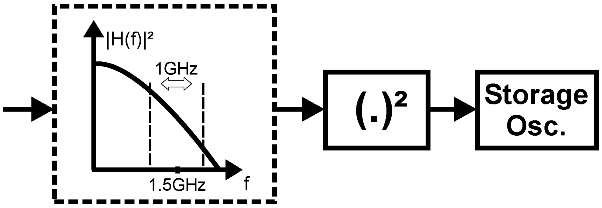

Fig. 2. Frequency discriminator consisting of a filter with linear edge around 1.5 GHz, a power detector, and a DSO.

II. MEASUREMENT SETUP

In theory, the frequency evolution of the laser can be monitored using a real-time coherent receiver. In order to track arbitrarily large deviations that are not limited by the signal processing algorithms, an external device was used for measurements. For this purpose, the output of the ECL was fed into a coherent optical polarization diversity receiver as pictured in Fig. 1.

An unmodulated optical signal was mixed down to an intermediate frequency of approximately 1.5 GHz using another identical ECL. The electrical analog signal of one of the four output diodes was then fed into a frequency discriminator that is shown in Fig. 2. The frequency discriminator consisted of a wideband filter with a linear falling edge around $f_0 = 1.5$ GHz. Any frequency deviation of each of the lasers led to a different output amplitude of the frequency discriminator filter that was then measured by a power detector and sampled in a digital storage oscilloscope (DSO). The DSO was triggered if a certain deviation of the input signal was observed. At a sampling frequency of $f_s = 10$ MHz, a time span of 0.2 s before and after the triggering could be recorded. Moreover, the polarization stability of the signal was assured. The recorded signal was

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M. Kuschnerov, K. Piyawanno, and B. Lankl are with the University of the Federal Armed Forces Munich, 85577 Neubiberg, Germany (e-mail: maxim.kuschnerov@unibw.de).

M. S. Alfiad is with the COBRA Institute, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands (e-mail: m.s.alfiad@tue.nl).

B. Spinnler and A. Napoli are with Nokia Siemens Networks, 80240 Munich, Germany (e-mail: bernhard.spinnler@nsn.com).

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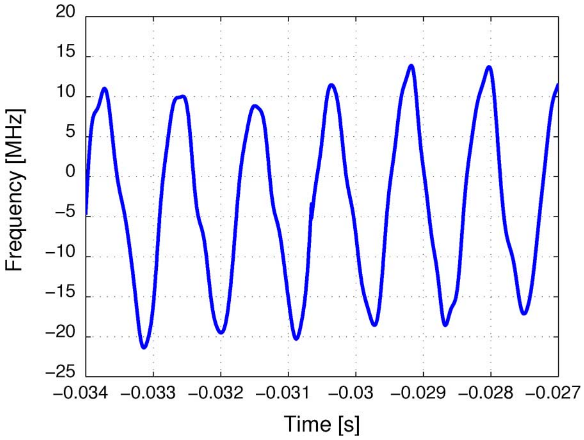

Fig. 3. Frequency evolution in steady state with $A_{\mathrm{pp}} < 40$ MHz and $\Delta f_0 \approx 1$ kHz.

postprocessed using low-pass filtering in order to smooth out the quantization noise of the DSO.

III. Local Oscillator Stability

As we have learned from microwave telecommunications in the past, several components in a communication system can cause phase noise degradation in the presence of vibrations, including coaxial cables, cable connectors, or narrowband filters [7]. In this experiment, the focus was on the local oscillator only. Here, mechanical vibrations cause small deformations of the electronic components, like the laser cavity, leading to phase fluctuations. The effect of vibrations on the laser phase evolution can be described as a frequency modulation. In order to simplify the evaluation and replication of the results, on a small scale we will model the frequency modulation by a sinusoid signal with a peak-to-peak amplitude of A_{pp} and a frequency Δf. The resulting evolution of the laser phase then reads as

$$y(t) = \sin\left(2\pi t\left(f_0 + \frac{A_{\mathrm{pp}}}{2}\sin(2\pi\Delta f t)\right) + \phi(t)\right) \quad (1)$$

where f_0 is the constant frequency offset between the transmitter and receiver lasers, and $\phi(t)$ is the general phase noise that is usually described as a random walk Wiener process. Even in a steady state with no vibrations, the frequency offset typically experiences a modulation, which in the case of the given lasers was $A_{\mathrm{pp}} < 40$ MHz and $\Delta f_0 \approx 1$ kHz, and is shown in Fig. 3. The frequency modulation is used in the given ECL as a cavity locking signal for the stabilization of the laser output. The phase evolution of the laser can, therefore, be modeled as a combination of a random walk and a manufacturer-dependent frequency modulation.

The frequency of the mixed-down signal was now measured for different cases of mechanical disturbance on the local oscillator laser. An example is shown in Fig. 4 that illustrates the general behavior of the frequency evolution.

Here, the local oscillator laser was lightly tapped by a metallic tool. At the relative time instant $t = 0$, the vibration occurs and the frequency experiences observable gradients of $A_{\mathrm{pp}} < 500$ MHz with $\Delta f_1 < 35$ kHz. After less than 0.1 s, the laser begins to stabilize. It can be observed how the frequency oscillates around the internal modulation frequency f_0 with $A_{\mathrm{pp}} < 40$ MHz and $\Delta f_{2a} = 13.8$ kHz for the given lasers.

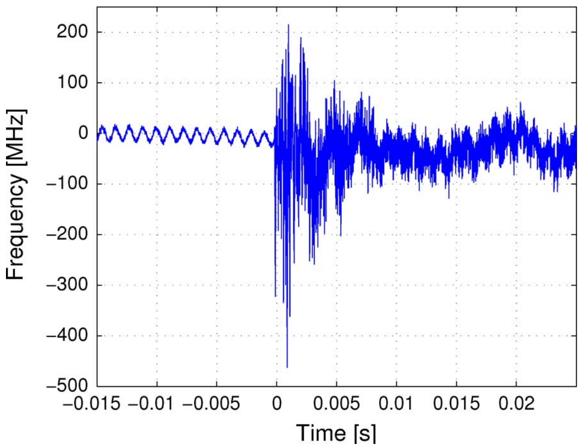

Fig. 4. Frequency evolution in case of a metallic tool tapping the laser at time instant $t = 0$.

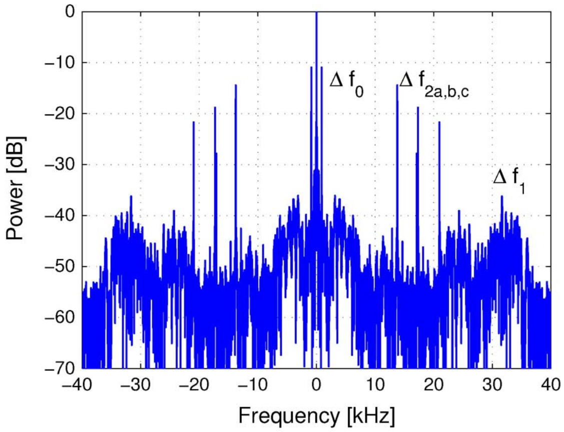

Fig. 5. Spectrum of the frequency evolution after the mechanical disturbance with the internal modulation frequency $\Delta f_0 = 886$ Hz and postvibration spectral components at $\Delta f_1 \approx 30$–35 kHz, $\Delta f_{2a} = 13.8$ kHz, $\Delta f_{2b} = 17.3$ kHz, $\Delta f_{2c} = 21$ kHz.

TABLE I

Local Oscillator Frequency Modulation Results for Different Mechanical Disturbances

Disturbance	A_{pp}	Δf
Metallic tool tap on the laser	<500MHz	<35kHz
Metallic tool tap on the receiver case	<350MHz	<35kHz
Wooden brush tap on the laser	<370MHz	<35kHz
Hand tap on the laser	<250MHz	≈ 1kHz
Hand hit on the table	<120MHz	≈ 1kHz

The exact frequency components can be observed in the spectrum view of the laser frequency evolution as shown in Fig. 5. The steady-state modulation of $\Delta f_0 = 886$ Hz can be observed, as well as the components around $\Delta f_1 < 35$ kHz. The characteristic frequency Δf_{2a} is accompanied by two other harmonics $\Delta f_{2b,c}$.

The frequency evolution depends on the kind of mechanical disturbance and is summarized in Table I for our measurements. Several measurements were performed for each setting with the largest observed frequency deviation listed in Table I.

It is apparent that the disturbance is only critical if the laser or its case are directly tapped. In general, the measured frequency deviation depends on the laser type and has to be measured for each system.

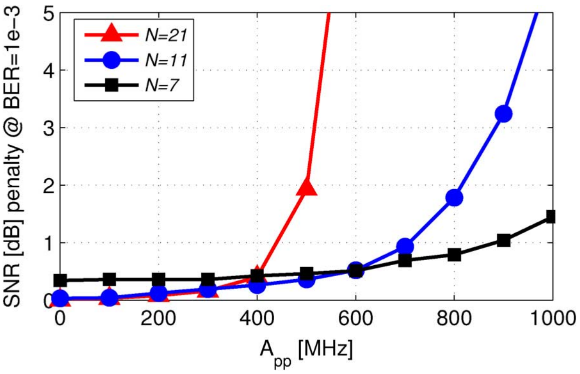

Fig. 6. Performance of 112-Gb/s PolMux QPSK versus the peak-to-peak frequency deviation $A_{\rm pp}$ at $\Delta f = 35$ kHz for the Viterbi & Viterbi phase recovery for several averaging block lengths N.

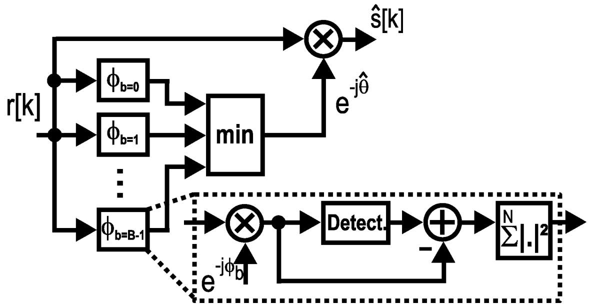

Fig. 7. Feed-forward minimum distance phase estimation for QAM [3].

IV. Receiver Impact

Signal processing usually includes a frequency offset compensator before carrier phase estimation. Depending on the precision of the frequency estimation, the impact of frequency deviations can be minimized, e.g., using data-aided methods. In the following, the performance of the carrier phase estimation alone will be analyzed, assuming a rather static frequency compensation. Carrier phase estimation for QPSK is typically performed using the Viterbi & Viterbi feed-forward algorithm, where a simplified version was used given by [2]

$$\hat{\theta} = \frac{1}{4}\arg\left\{\sum_{k=0}^{N-1} r^4[k]\right\} \tag{2}$$

where $r[k]$ is the received signal and N is the averaging length. The bandwidth of the estimation was set by varying N. The performance of the algorithm against frequency variations is demonstrated in Fig. 6 for 112-Gb/s polarization multiplexed (PolMux)-QPSK with typical filter settings and a 100-kHz laser linewidth for transmitter and receiver lasers. At the given rate, QPSK is very tolerant against frequency deviations and does not experience a penalty for $A_{\rm pp} < 500$ MHz, if the averaging block length N of the estimation is chosen small enough, in order to yield a higher bandwidth of the estimator.

Naturally, the performance deteriorates once higher order modulation is taken into account. Feed-forward phase estimation for QAM was proposed in [3] and shown in Fig. 7.

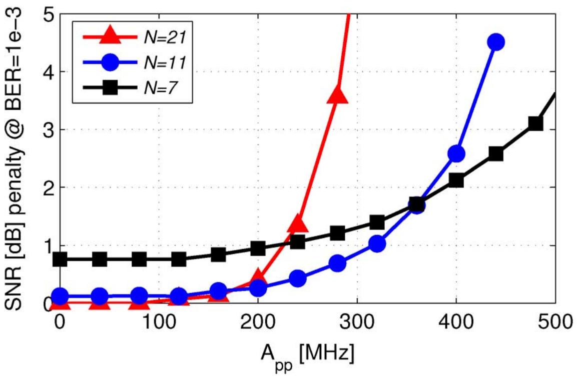

Fig. 8. Performance of 224-Gb/s PolMux 16 QAM versus the peak-to-peak frequency deviation $A_{\rm pp}$ at $\Delta f = 35$ kHz.

Fig. 8 analyzes the performance in the presence of frequency deviations. Here, the maximum measured frequency deviations cannot be tracked without penalty if $\Delta f = 35$ kHz and would either lead to an outage for large N or to a sensitivity penalty for small N.

V. Conclusion

The frequency evolution in the presence of vibrations of a typical laser used in coherent optical high-speed communications was analyzed. The observed frequency deviations for the given laser were up to 500 MHz with a modulation frequency of up to 35 kHz of the carrier. The impact on the carrier phase estimation was numerically analyzed for 112-Gb/s PolMux-QPSK and 224-Gb/s PolMux-16 QAM. It was found that the feed-forward estimation algorithm for 16 QAM could not track the maximum observed deviations, which occurred when the laser was directly tapped, whereas QPSK remains penalty-free. However, if the mechanical vibration is not directly at the laser, assuming certain isolation, the modulation frequency of the carrier remains identical at the steady-state value of around $\Delta f \approx 1$ kHz, which can be easily compensated using standard carrier phase estimation algorithms.

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