

Impact of laser linewidth on Free Space Optical communications performances

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ABSTRACT

Free-space optical communication is a promising technology for next-generation satellite systems, offering high data rates, low size, weight, and power, and enhanced spectral efficiency. The performance of optical communication links is influenced by the spectral properties of the employed laser sources, particularly their linewidth. This work presents an experimental investigation of the impact of laser linewidth on the bit error rate (BER) performance of optical communication systems relevant to satellite applications.

Two laser technologies are investigated, distributed-feedback (DFB) and external-cavity lasers (ECLs), covering linewidths ranging from below 10 kHz to hundreds of MHz. Their spectral characteristics are evaluated using two different self-heterodyne measurement techniques, including a delayed configuration and a short-delay approach for narrow-linewidth characterization. The measured laser sources are then employed in communication experiments using OOK, DPSK, and dual-polarization QPSK modulation. Controlled linewidth broadening is also introduced to extend the experimentally accessible range and quantify the resulting performance penalties.

The measurements demonstrate the different linewidth tolerance of intensity- and phase-sensitive modulation formats, with increasing sensitivity observed for higher data rates and coherent modulation. These results provide practical guidelines for laser selection and linewidth optimization in high-capacity free-space optical satellite communication systems.

Keywords: Free Space Optical Communications, satellite communications, laser linewidth, phase noise, coherent detection, phase modulation.

1. INTRODUCTION

Photonic technologies are transforming satellite communications [1] by complementing or replacing traditional RF systems with fiber optics, free-space optics, and integrated photonics solutions to reduce size, weight, and power (SWaP) in a wide range of applications. In particular, future satellite systems will utilize free-space laser communication and Wavelength Division Multiplexing (WDM) to achieve higher throughput, discretion, and security through long-distance optical beams. Such high-capacity free-space optical (FSO) links will interconnect satellites in constellations, proving essential for the global delivery of broadband communication services and advanced Earth observation missions. Other applications of FSO links include ground-to-space communications, direct-to-the Earth LEO downlinks, data relay, synchronization and ranging as well. Photonic technology is also considered for RF signal generation and handling subsystems on board of telecommunication and/or observation satellites. These applications call for laser sources that should, very often simultaneously, satisfy strict spectral purity and linewidth, wavelength tenability and stability, output power and system-level integration constraints [2]. Various and different modulation formats and detection modes are being deployed or considered, from OOK and DPSK with direct/differential detection, to coherent QPSK or x-QAM with intradyne detection [3,4] at different baud rates, which poses a large range of requirements [5].

Semiconductor lasers are often distinguished by the structure of their optical cavities. [6-8]. Distributed Feedback (DFB) lasers integrate a microscopic Bragg grating directly into the active region, forcing single-mode emission with excellent wavelength stability but limited tunability, relatively high output power [6] and moderate linewidth, which has made them a robust, cost-effective solution in particular for long-haul optical fiber communications. On the other hand, External-Cavity Lasers (ECLs) combine a semiconductor gain chip with external optical elements, such as a bulk diffraction grating

or preferably an integrated silicon-photonics microring resonator. This extended cavity provides wide, continuous wavelength tuning and dramatically reduces phase noise resulting in very narrow linewidth. Tunable ECLs can thus play an essential role, by offering the tuning flexibility and spectral purity needed to push the performance limits in coherent optical communications, and photonic RF processing subsystems.

In this study, we investigate the impact of the laser linewidth on the BER performance of optical communication links employing various modulation formats commonly used or considered in satellite communications. In this paper, we first present and compare two methods for laser linewidth measurement. We then report on an experimental campaign for linewidth and performance measurement on two different types of lasers, namely DFB and ECL, for different modulations including differential phase-shift keying (DPSK) and quadrature phase-shift keying (QPSK). The experimental results are analyzed together with laser phase noise theoretical model and are further compared by numerical simulations.

2. LASER LINEWIDTH CHARACTERIZATION

Lasers

A set of laser sources including both DFB lasers and External Cavity Lasers (ECLs), covering a wide range of linewidth characteristics, was selected. The objective of this characterization was not only to determine the optimal operating conditions of the lasers but, more importantly, to identify and quantify the linewidth range available for the subsequent communication experiments. The selected laser sources and their main characteristics are summarized in Table 1.

The tested laser set comprises eight devices representing two main architectures: DFB lasers and External Cavity Lasers. Five DFB lasers were sourced from suppliers A, B, and D, while three ECLs were sourced from supplier C. The DFB chips supplied by vendor B were developed by III-V Lab. The diversity of suppliers and laser architectures provides a representative basis for performance assessment and benchmarking.

DFB lasers incorporate a distributed-feedback grating within the semiconductor cavity, providing a compact, reliable, and cost-effective solution with moderate linewidth performance. ECLs, on the other hand, employ an external optical resonator to enhance wavelength selectivity, resulting in narrower linewidths, lower phase noise, and improved frequency stability. Consequently, ECLs generally offer superior spectral performance, whereas DFB lasers benefit from lower cost, smaller size, and greater integration.

The electrical and optical characterization of the DFB lasers was performed to determine the operating points used during the FSOC experiments. In particular, L-I measurements were carried out to identify the threshold current, slope efficiency, and achievable output power of each device. The device temperature was maintained at 25°C while the emitted optical power was monitored using an external optical power meter. The resulting L-I characteristics are presented in Figure 1. The optical spectra are also shown in Figure 1 alongside the corresponding L-I measurements.

The results confirm that the investigated DFB sources operate within the required wavelength range, with emission wavelengths approximately between 1536 and 1555 nm depending on the device. Although these lasers do not provide the wavelength flexibility offered by ECL modules, limited wavelength tuning can be achieved through adjustments of the injection current and operating temperature.

Id	Supplier	Type	Current Range	Operating λ	Threshold current	Max. output power
881	A	DFB butterfly	0-350 mA	1552.71 nm	55 mA	40 mW
885	A	DFB butterfly	0-350 mA	1554.25 nm	50 mA	30 mW
T1	B	DFB butterfly	0-700 mA	1536.75 nm	50 mA	78 mW
T5	B	DFB butterfly	0-700 mA	1536.91 nm	60 mA	100 mW
4	C	External cavity	n/a	Tunable	n/a	32 mW
5A	C	External cavity	n/a	Tunable	n/a	32 mW
5B	C	External cavity	n/a	tunable	n/A	32 mW
6	D	DFB				100 mW

Table 1. Laser sources with respective characteristics

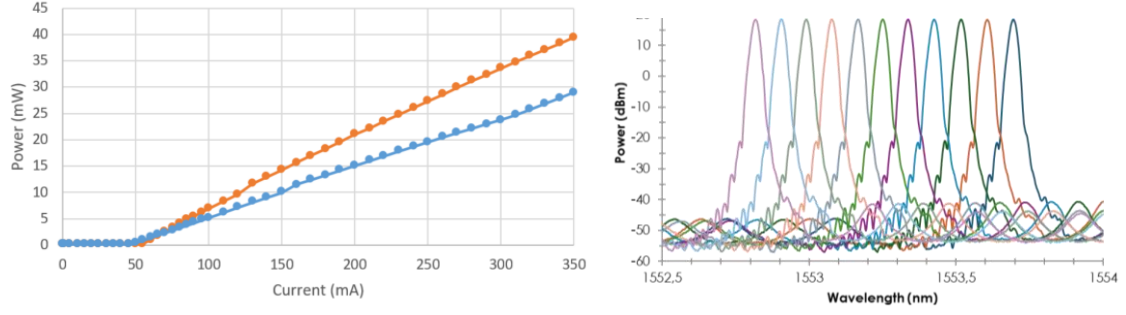


Figure 1. Example of L-I curve for DFB supplier A (commercial) and their optical spectra

Set-up

Various techniques have been proposed to measure laser linewidth, including optical spectrum analysis, heterodyne beat-note measurements, and delayed self-homodyne/self-heterodyne methods. Among these approaches, the delayed self-heterodyne technique introduced by Okoshi et al. [10] remains one of the most widely used methods for narrow-linewidth lasers. Nevertheless, linewidth characterization is not straightforward, as the measured linewidth may depend on the laser frequency-noise spectrum and the observation time. Mercer showed that low-frequency $1/f$ noise can have a significant impact on the measured linewidth, highlighting the importance of properly interpreting linewidth measurements [11].

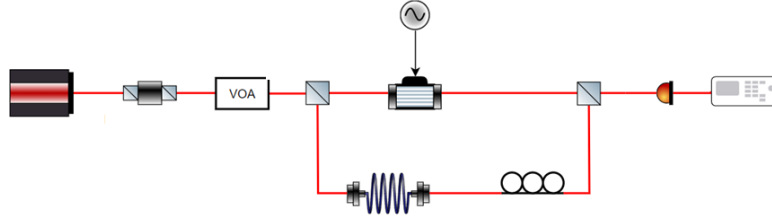


Figure 2. Laser self-heterodyning set-up for spectral linewidth characterization

Measurements have been conducted to determine the linewidth of the different lasers using a self-heterodyne setup [12], shown in Figure 2. The laser output was first routed through an optical circulator, which acted both as an optical isolator to suppress back-reflections into the laser cavity and as a means of monitoring the reflected power returning from the photodiode. The optical signal was then divided into two separate branches. The first branch included an acousto-optic modulator (AOM), driven by a reference signal generated by an analog signal generator and amplified using an RF amplifier. The AOM introduced the corresponding frequency shift to the optical signal. The second branch consisted of an optical fiber delay line followed by a polarization controller, which was adjusted to maximize the output power. The two optical paths were then recombined using a coupler, and the resulting signal was sent through a variable optical attenuator (VOA) to regulate the optical power incident on the photodiode.

In the first method, the generated photocurrent was acquired using an oscilloscope. The optical frequency noise in Figure 3 was extracted by applying a numerical Fourier transform to the acquired time-domain beat-note signal [13]. From the measured noise floor, the instantaneous Lorentzian linewidth of our laser, i.e., the fundamental linewidth, is determined by the relation $\Delta\nu_f = 2\pi NF^2$ [14][15], where NF denotes the noise floor level. Note that the formula differs from the expression reported in [14] by a factor of 2 which arises from the use of an oscilloscope to extract the frequency noise. In this configuration, both positive and negative frequency components contribute, requiring factor 2 to account for the total energy. This gives a linewidth of 40 kHz.

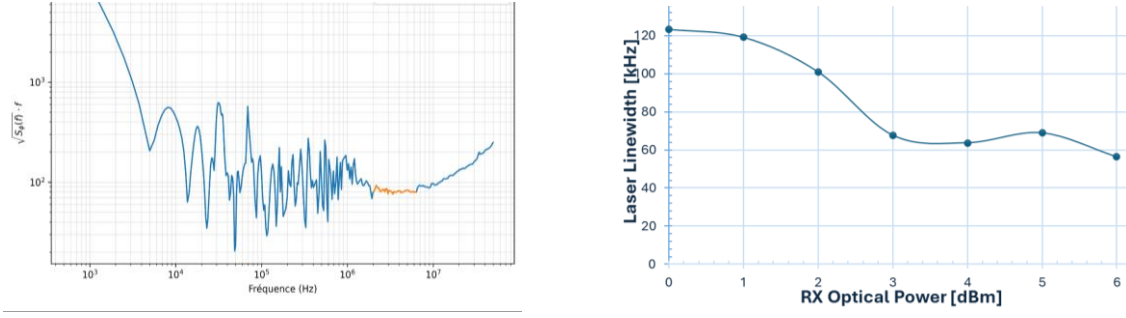


Figure 3. Method 1 a) optical frequency noise and b) sensitivity to optical input power

As previously stated, the characterization of narrow-linewidth lasers requires dedicated measurement techniques. In the conventional delayed self-heterodyne method, it is typically necessary to employ a delay line at least six times longer than the coherence length of the laser to ensure that the resulting beat note exhibits a purely Lorentzian shape [16], as $\Delta f = 1/\pi\tau_c$ being τ_c the coherence time of the laser. In the approach described earlier, this requirement is relaxed due to the use of software-based compensation, allowing the use of relatively short delay lengths on the order of 1-3 km of optical fiber. In this work, an alternative approach is also considered for the characterization of narrow-linewidth lasers, namely the short-delay self-heterodyne technique. In contrast to long-delay implementations, this method avoids the use of excessively long fiber spools, which are known to introduce significant $1/f$ noise contributions [17]. Such noise leads to spectral broadening of the measured beat note and can introduce substantial errors in the extracted linewidth. Although fitting schemes have been proposed for long-delay configurations, the influence of $1/f$ noise cannot be fully eliminated, making short-delay implementations more suitable for accurate linewidth estimation.

The setup is shown in Figure 2. Here, fiber length is approximately 20 m long. The polarization controller is used to maximize interference visibility before the two arms are recombined using a Y-branch coupler. The resulting signal is analyzed using an Electrical Spectrum Analyzer (ESA).

For short delay times, the measured beat note exhibits a characteristic envelope function with periodic maxima and minima, arising from the partial coherence between the two arms of the interferometer. This behavior reflects the finite coherence time of the laser, as the interference signal depends on the degree of phase correlation between the delayed and frequency-shifted optical fields. The linewidth evaluation can be done by studying different combinations of maxima and minima in the recovered signal through the following expression [16] as seen on Figure 6.

$$\Delta s = 10 \log_{10} S_H - 10 \log_{10} S_L = 10 \log_{10} \frac{\left[\Delta f^2 + \left[\frac{(k+2)c}{2nL} \right]^2 \right] \left[1 - e^{-2\pi \frac{nL}{c} \Delta f} \cos[(m+2)\pi] \right]}{\left[\Delta f^2 + \left[\frac{(m+2)c}{2nL} \right]^2 \right] \left[1 - e^{-2\pi \frac{nL}{c} \Delta f} \cos[(k+2)\pi] \right]} \quad (1)$$

Where Δs is the difference between a maximum and a minimum of the side lobes of the function and m and k represent the order of the maxima and the minima starting from the center frequency, noting that $m \neq k$, and if two extrema are adjacent, $|k - m| = 1$. The following measurements have been carried out.

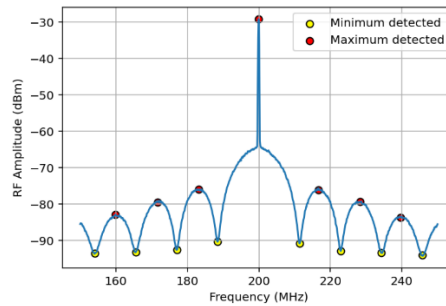


Figure 4. Method 2 Electrical Spectrum

Results

Figure below shows the estimated linewidth of laser B_T1 as a function of injection current using two different measurement methods. Both methods exhibit a similar overall trend, with a minimum linewidth of approximately 40-50 kHz observed around 180-200 mA. As the injection current increases beyond this optimum operating region, the linewidth gradually increases and reaches values above 150 kHz. Although some discrepancies are observed between the two estimation methods, particularly at intermediate current levels, the overall behavior remains consistent and indicates a strong dependence of the linewidth on the operating current. The other graph presents the estimated linewidth of the external cavity laser C_id4 as a function of optical output power. In contrast to the DFB sources, the ECL exhibits a very narrow linewidth, ranging from approximately 10 to 15 kHz over the investigated power range. The linewidth remains essentially constant with optical power, and both estimation methods provide nearly identical results. These measurements confirm the superior spectral purity and stability typically associated with external cavity laser architectures.

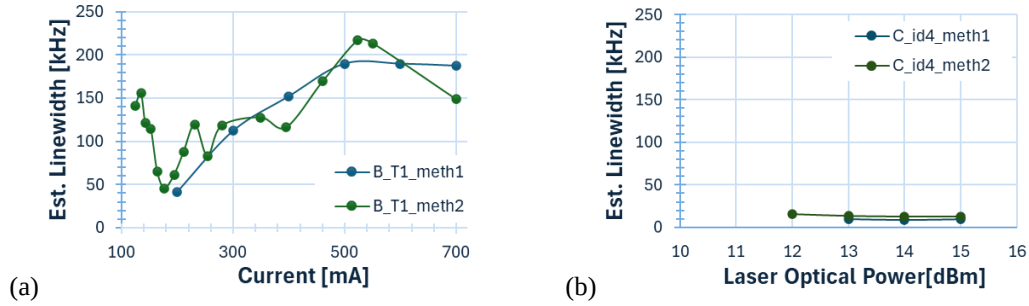


Figure 5. Comparison of linewidth measurement methods for 2 types of laser: (a) DFB laser : (b) external cavity lasers

Table below summarizes the linewidth values measured for all investigated laser sources. Significant differences are observed between the tested devices, with linewidths spanning more than four orders of magnitude. The external cavity lasers supplied by vendor C exhibit the best spectral performance, with linewidths below 15 kHz and reaching values below 10 kHz for sample C/id5B. The DFB lasers from suppliers A and B show intermediate linewidth values ranging from approximately 100 to 200 kHz. Among these devices, samples A/881 and A/885 exhibit linewidths close to 120 kHz, while samples B/T1 and B/T5 present larger linewidths of 207 kHz and 153 kHz, respectively. These results illustrate the variability that can exist between DFB laser designs and operating conditions. Figure 6 further shows that the linewidth depends only weakly on the optical output power, with values remaining stable between approximately 5 and 14 kHz. These results confirm the excellent spectral purity and stability of the investigated ECL sources.

Table 2. linewidth results

Laser	A/881	A/885	B/T1	B/T5	C/id4	C/id5A	C/id5B	D
Linewidth (kHz)	111	121	207	153	< 15	< 15	<10	100s of MHz

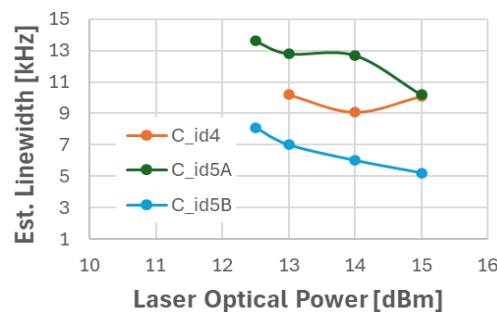


Figure 6. linewidth comparison for several units of external cavities (same part number)

3. IMPACT ON THE DIGITAL COMMUNICATION PERFORMANCE

Random phase fluctuations in the optical field transmitted from laser sources, primarily driven by spontaneous photon emission, resulting in a finite laser linewidth. These fluctuations are commonly modeled as a Wiener process [18]. Under this assumption, the phase error variance accumulated over one symbol period is given by $\sigma_\theta^2(\Delta\nu) = 2\pi\Delta\nu T$ where $\Delta\nu$ denotes the laser linewidth and T is the symbol duration. For coherent detection, the effective linewidth corresponds to the sum of the linewidths of the transmitter laser $\Delta\nu_T$ and the local oscillator $\Delta\nu_{LO}$, while for non-coherent detection schemes, where no local oscillator is employed, the effective linewidth is determined only by the transmitter laser $\Delta\nu_T$.

This phase uncertainty directly affects the received constellation by introducing random rotations of the transmitted symbols. As the linewidth increases, the phase variance also increases, reducing the receiver's ability to correctly distinguish between adjacent constellation points. Consequently, modulation formats relying on phase encoding and coherent detection exhibit a larger sensitivity to laser linewidth than intensity-modulation format with direct detection.

The transmission experiments were performed using a modulation/demodulation unit incorporating a pre-amplified receiver based on a low-noise optical amplifier (LNOA). Pseudo-random binary sequence (PRBS) data were used to generate the transmitted signal. System performance was assessed through bit error rate (BER) measurements as a function of the received optical power, measured at the input of the LNOA. For each experimental condition, the received power was progressively varied and the corresponding BER was recorded. This procedure was repeated for different laser linewidth values in order to quantify the performance penalties associated with increased phase noise. Two modulation formats were investigated. On-Off Keying (OOK) relies on direct amplitude modulation and direct detection at the receiver. Differential Phase-Shift Keying (DPSK), on the other hand, encodes information in the phase difference between consecutive symbols and was demodulated using a self-homodyne interferometric receiver followed by a balanced photodetector.

The expected degradation in FSOC system performance becomes significant only for larger linewidths, typically in the megahertz range. Consequently, the intrinsic linewidth tuning provided by the available laser sources is insufficient to experimentally investigate the full range of linewidth induced penalties predicted by the system analysis. To overcome this limitation and enable a controlled evaluation of linewidth effects over a wider range, an artificial linewidth broadening technique has been implemented. This approach consists of introducing additional phase noise into the laser by superimposing a white noise signal onto the injection current. Experimentally, this was achieved by connecting the modulation input of the laser driver to an external white noise source via a BNC interface on the current source that biases the different lasers. The corresponding results demonstrate a significant broadening of the linewidth as a function of the applied noise level. In particular, the DFB lasers provided by supplier A exhibit a tunable linewidth that can be extended up to the order of tens MHz under these conditions. This technique enables access to a wider linewidth range, thereby allowing a more comprehensive investigation of the relationship between laser coherence properties and optical communication system performance.

OOK transmission experiments were carried out at data rates of 10 and 25 Gbps, whereas DPSK transmission was investigated at 25 Gbps only. A DFB laser supplied by vendor A was used as the optical source. To assess the impact of laser phase noise on transmission performance, the laser linewidth was artificially broadened over a wide range of values.

The BER measurements as a function of received optical power, and their corresponding power penalty (additional received optical power required by the system affect by an increased laser linewidth to achieve the same BER performance as the reference case) are presented in Figure 7 for different linewidth values. The results show that the system remains largely insensitive to laser linewidth variations up to approximately 50 MHz, where the systems received power should be more than doubled in order to maintain a BER of 10^{-10} . To further illustrate the influence of laser linewidth on signal quality, no significant differences in the eye opening or overall eye shape are observed, indicating that the OOK system remains largely unaffected by linewidth variations within this range.

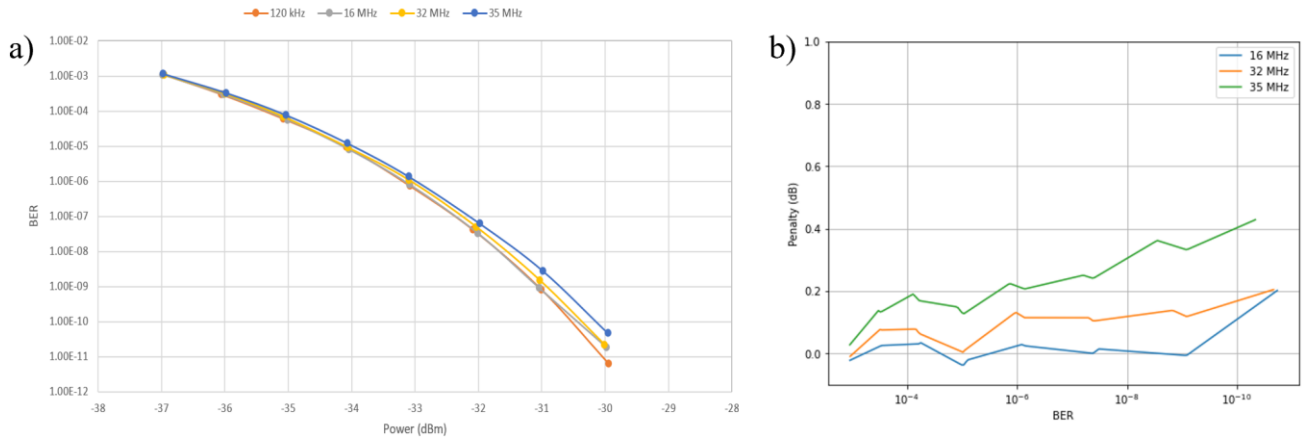


Figure 7. Impact of laser linewidth on BER performance in OOK (a) BER as a function of received optical power; (b) power penalties at various BER as a function of laser linewidth

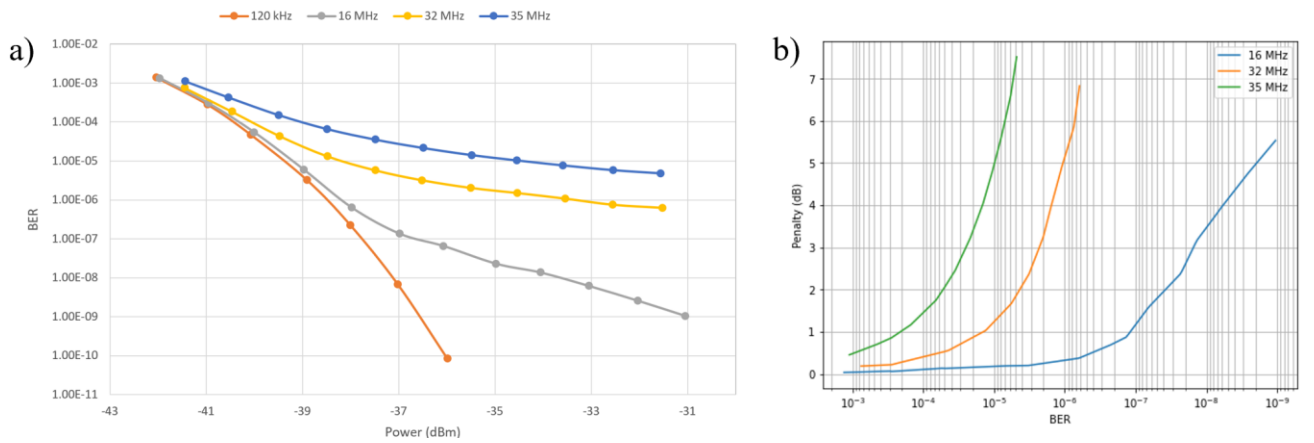


Figure 8. Impact of laser linewidth on BER performance in 25 Gbps DPSK transmission (a) BER as a function of received optical power; (b) power penalties at various BER as a function of laser linewidth.

In the case of coherent transmission, the transmitter consists of integrated modulators and an external laser. At the receiver, a local oscillator laser is combined with an integrated coherent receiver. A real time scope acquires the signal that is then post-processed offline. The analysis is performed for data rates up to 100 Gbps for DP-QPSK modulation. Details of the set-up are given in Ref. [9]. Experimental evaluations are carried out using different laser types from multiple suppliers, enabling linewidth tuning via bias current adjustment, covering a range from some kHz to MHz

Figure below show the optical spectra of two lasers from reference C/id4 and reference D. Their respective constellation is also shown. The constellation from laser D is clearly degraded.

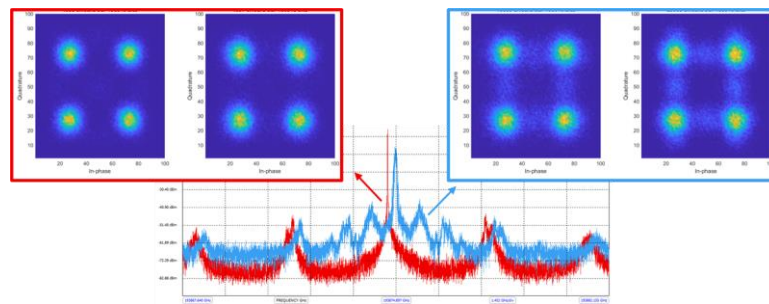


Figure 9 Effect of linewidth on DP-QPSK constellations

4. CONCLUSION

The laser linewidth is of particular interest, as it directly determines the phase noise of the optical carrier, influencing the quality of the transmitted signal and ultimately the overall communication performance. To investigate these effects, both theoretical and experimental analyses are performed using modulation formats widely employed in modern satellite communication systems namely OOK, DPSK, QPSK. Different packaged laser sources, with different linewidths, are employed as optical carriers, allowing the assessment of the relationship between laser linewidth properties and communication system performance. Metrics such as the BER, eye diagrams, and constellation diagrams are analyzed to quantify the impact of linewidth under different operating conditions. The influence of linewidth on system-level performance is analyzed through OSNR versus BER and BER versus bit rate (R_b) for different linewidth values. These results highlight the potential for improving system flexibility in terms of OSNR requirements and achievable data rates by optimizing laser linewidth. Overall, this work provides a comprehensive assessment of linewidth-induced impairments in FSO satellite links and offers practical guidelines for laser selection and system design in next-generation high-capacity optical communication systems.

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