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Abstract *Frequency combs can replace multiple lasers in WDM systems. We highlight performance requirements for frequency combs in coherent communications and present recent results using Kerr combs for multi-Tb/s transmission using advanced modulation formats.*

Introduction

The spectrum of a laser frequency comb consists of multiple and equidistant optical frequencies that maintain a fixed phase relation. The absolute location of the lines is set by two frequencies i.e., the repetition rate, f_r, which defines the spacing between consecutive comb lines, and the offset, f_0, which defines the frequency shift of the comb with respect to an ideal ruler of frequencies evenly spaced by the repetition rate.

Key developments during the late 90s facilitated phase locking these two frequencies to atomic radio-frequency references, thereby establishing a coherent and bi-directional link between the optical and microwave domains. This allowed to operate the frequency comb as an optical synthesizer, whereby virtually any frequency within the laser spectrum could be generated with the accuracy and precision provided by electronics. Vice versa, a laser frequency comb provides the optical clockwork necessary to count the cycles of optical frequency standards and establish a comparison with radio-frequency references. The core of a laser frequency comb is typically a mode-locked laser delivering ultrafast optical pulses at a rate commensurate to the free spectral range of the cavity. The cavity length and gain elements are actuated to stabilize the two degrees of freedom mentioned above.

Some of the key enabling features of a laser frequency comb are: (i) multiple frequencies are simultaneously available from a single laser; (ii) the line spacing is equidistant and can be locked to a stable microwave frequency; (iii) phase coherence is maintained across the bandwidth, and (iv) the optical lines can be known with a relative uncertainty to the 10^{-17} level[1].

Optical frequency combs also offer unique opportunities in fiber-optic communication systems. In wavelength division multiplexing (WDM) for example, see Fig. 1, a single frequency comb could replace hundreds of lasers[2-4] both at the transmitter and receiver side[5]. The tight frequency locking between lines alleviates the need for wavelength control at the individual channel level and enables a dramatic increase in spectral efficiency by eliminating the channel guardbands[6]. In addition, frequency locking has proven key to mitigate inter-channel nonlinear cross-talk by digital pre-compensation[7]. Another exciting aspect of laser frequency combs is the possibility to exploit the broadband phase coherence among channels to simplify the digital signal processing chain at the receiver side by performing joint impairment compensation[8]. These aspects are enabled by the unique features of frequency combs and are difficult, if not impossible, to implement with an array of individual lasers.

The requirements of a laser frequency comb in WDM systems are very different to the requirements for other metrology applications. Absolute accuracy with 17 digits of precision is not needed but the comb's repetition rate must be equal to the channel spacing, which is in the order of 10-100 GHz and therefore difficult to attain with standard mode-locked lasers. In addition, for practical purposes, a WDM transceiver should be integrated on a photonic chip. The need for an integrated comb to light simultaneously hundreds of WDM channels raises concerns with regards to the minimum optical signal to noise ratio (OSNR) and power per line that can be obtained. The purpose of this contribution is to revisit quantitative benchmarks for coherent communications that illustrate some of the challenges involved. We will highlight our recent results showing multi-Tb/s data transmission using high-order complex modulation formats (PM 64-QAM) encoded onto the lines of a Kerr microresonator comb[9]. These results indicate these integrated comb sources are reaching a significant maturity level and may become serious contenders for practical applications in WDM.

Performance requirements of laser frequency combs in WDM systems

Let us consider a WDM system like the one sketched in Fig. 1, where a single polarization is depicted for simplicity. At the transmitter side, the individual channels are given by the frequency lines of an optical frequency comb. The lines are
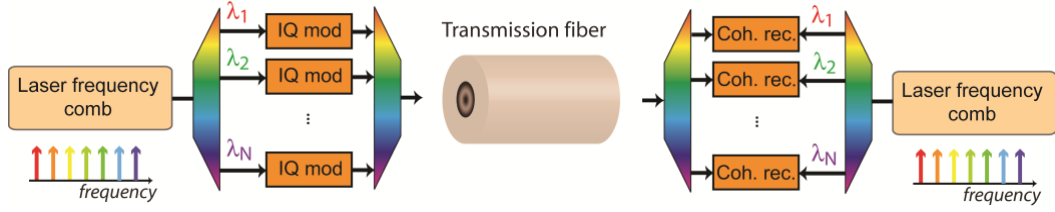
Fig. 1: Schematic representation of a WDM transceiver where the multi-wavelength laser array at both transmitter and receiver sides are implemented by a laser frequency comb.

modulated in amplitude and phase, and subsequently multiplexed to generate the signal transmitted through the fiber link. At the receiver side, the channels are demultiplexed. Each WDM channel is measured with the aid of a coherent receiver (only hardware components depicted for simplicity). The required local oscillator lasers are replaced by another frequency comb, whose line spacing and offset are matched to the transmitter side's comb.
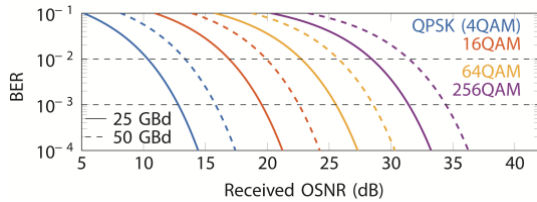

Fig. 2: Bit error ratio as function of received optical signal to noise ratio (0.1 nm bandwidth) for different modulation formats and symbol rates. Simulations assume Gray coding and additive white Gaussian noise.

External cavity tunable lasers typically have optical powers in the order of 100 mW, instantaneous linewidths below 100 kHz and side-mode supression ratios > 50dB. The optical power and signal to noise ratio are not the main limiting factor when used as WDM sources. The situation is different when the WDM channels are provided by an optical frequency comb. Figure 2 shows the achievable bit error ratio (BER) when varying OSNR for different modulation formats and symbol rates. It is interesting to note that doubling the baud rate or increasing 2 bits per symbol requires 3dB extra in received OSNR at a BER threshold of 10^{-3}. The examples are better illustrated in Table 1, where the minimum required OSNR is supplemented with the linewidth requirements. Essentially, OSNRs ~ 30-40 dB per line and ~100 kHz linewidth are needed for high-order (64-QAM and beyond) modulation formats. This performance level can be reached with bulky electro-optic frequency comb generators but it is challenging to attain with an integrated comb source that is aimed to cover a broad bandwidth and large number of lines.

PM-64QAM experiments with microresonator frequency combs
Over the last decade, there has been tremendous

progress in integrated frequency comb sources in the 1.5 μm window. A very promising type of integrated frequency comb are microresonator (or Kerr) frequency combs. The comb is generated by tuning a single frequency laser into the longitudinal mode of a high-Q microcavity, building up the power and allowing for the generation of a multitude of frequencies via four-wave mixing and soliton generation[10]. The attractiveness of microresonator combs for optical communications is that the line spacing is defined by the free spectral range of the cavity, which can easily reach 100 GHz for millimeter long cavities, and the fabrication techniques are compatible with silicon photonics using e.g. silicon nitride microresonators. More importantly, the bandwidth can be accurately controlled by engineering the dispersion of the cavity. Recent experiments have demonstrated advanced coherent communications with WDM carriers provided by a temporal cavity soliton generated in a silicon nitride microresonator comb covering the C & L bands with 100 GHz spacing[5]. These experiments nicely illustrated that the inherent parallelism of frequency combs could be exploited at the transmitter and receiver sides.

Tab. 1: Minimum requirements per wavelength and polarization channel for different modulation formats. The linewidth refers to the maximum instantaneous bandwidth that can be tolerated before an OSNR penalty of 0.2dB is incurred. The OSNR at the transmitter is calculated from Fig. 2 for a BER threshold of 10^{-3}. The values here include a more realistic transceiver with 5 ENOBs[11].

Modulation format	Symbol rate (GBd)	Linewidth (kHz)	Tx OSNR (dB) @ 0.1 nm RBW
16 QAM	25	430	20.6
	50	860	23.6
	100	1720	26.6
64 QAM	25	125	27.1
	50	250	30.1
	100	500	33.1
256 QAM	25	37.5	34.4
	50	75	37.4
	100	150	40.4

We have recently investigated the use of mode-locked dark pulses in silicon nitride microresonators[12] for coherent optical communications[9]. These dark pulses are different to temporal cavity solitons in that they operate in the normal dispersion regime and
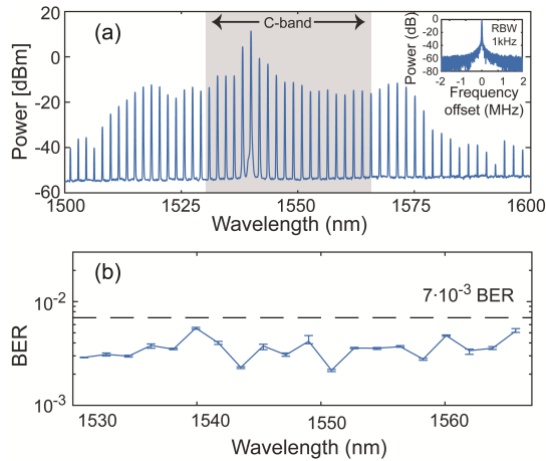
Fig. 3: (a) Optical spectrum of a 230 GHz microresonator comb. Inset denotes the line spacing stability measured by electro-optic downconversion. (b) Achieved BER upon propagation in 80 km single-mode fiber when encoding 20 GBd PM-64QAM data onto individual the comb lines within the C band[9].

display much higher pump to comb power conversion efficiency. This is an important characteristic in fiber-optic coherent communications because it allows to achieve high OSNRs while maintaining a laser pump power commensurate to the levels provided by hybrid silicon lasers. Figure 3 shows the optical spectrum of the microresonator comb with an on-chip coupled power of ~20 dBm. The inset is the measured RF beat between two consecutive lines, indicating mode-locking operation and a stability level beyond what could be obtained with independent standard tunable lasers. With conversion efficiencies in the order of 20%, we achieved WDM signals with an OSNR of 33 dB after channel equalization and amplification. The linewidth of the comb lines was measured below 10 kHz. Altogether, such performance allowed us to successfully encode polarization multiplexed 64 QAM onto all the comb lines (see Fig. 3), yielding an aggregate data rate of 4.4. Tb/s. These results represent the highest modulation complexity ever encoded on an integrated frequency comb source.

Conclusions

Laser frequency combs provide unique opportunities in fiber-optic communication systems. The broadband phase coherence, frequency spacing stability and multitude of lines from a single laser source enable system-level performance enhancements beyond what is possible with an array of independent tunable lasers. Notwithstanding, practical WDM systems introduce stringent constraints with regards to OSNR and linewidth that are difficult to attain with integrated laser frequency combs. Micro-resonator combs offer an opportunity to achieve WDM channels with a sufficient OSNR to encode complex modulation formats and yet keep a pump power level compatible with silicon photonic hybrid lasers.

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