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Filter Optimization for Self-Homodyne Coherent WDM Systems using Interleaved Polarization Division Multiplexing

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Abstract—We examine the impact of filtering on self-homodyne coherent WDM systems using the interleaved polarization division multiplexing scheme. To investigate the performance limit and to provide more insight into previously obtained experimental results we perform numerical simulations in which different filter shapes and filter bandwidths are used. It is shown that with proper prefiltering of the data and filtering of the pilot tone in the receiver, performance can approach that of an intradyne system. This would make it possible to implement coherent systems with high spectral efficiency without any digital signal processing in the receiver.

Index Terms—coherent detection, OSNR, self-homodyne, intradyne, QPSK, polarization division multiplexing, spectral efficiency, pilot tone, wavelength division multiplexing.

I. INTRODUCTION

MULTILEVEL modulation formats make it possible to increase the spectral efficiency and will be an indispensable part of future fiber-optical networks. Currently, major efforts are focused on formats that carry information in the phase of the optical field, such as quadrature phase-shift keying (QPSK), or in both amplitude and phase, such as 16-quadrature amplitude modulation (16-QAM). While it is possible to demodulate these formats by using differential detection [1], the highest sensitivity is obtained when coherent detection is used. This means that a phase reference needs to be provided in the receiver. The conventional way to implement coherent detection in fiber optic systems is to use a local oscillator (LO) laser in the receiver and mix its output with the signal during

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photodetection. Digital signal processing (DSP) is then used to track the frequency offset between the lasers and the relative phase drift due to laser phase noise. This approach is known as intradyne coherent detection and requires lasers with narrow linewidths [2] and high speed electronics [3]. Very high spectral efficiencies have been demonstrated by using a combination of intradyne detection, polarization division multiplexing (PDM), QAM, and offline data processing [4-8].

While the performance of intradyne systems is very promising, other methods to implement coherent detection exist. One example is to use self-homodyne coherent detection [9], in which a co-propagated pilot tone orthogonally polarized relative to the signal is used as phase reference in the receiver. This scheme is known to be extremely linewidth tolerant and real-time bit error rate (BER) measurements have been demonstrated for 10 Gbaud 16-QAM [10] and 5 Gbaud 64-QAM signals [11]. The impact of polarization-mode dispersion (PMD) on self-homodyne systems has also been investigated [12]. These experiments highlight the possibility to use advanced modulation formats without having to develop a high-speed application-specific integrated circuit for the receiver. Tasks such as chromatic dispersion compensation and clock recovery can be performed without DSP, but the phase recovery cannot be avoided in a system using intradyne detection since every laser has a non-zero linewidth. While the possibility to perform coherent detection without DSP is interesting, pilot tones can also be used to improve the performance of a digital coherent receiver. Recently, Okamoto et al. demonstrated 512-QAM transmission in which the DSP-based phase recovery was aided by a co-transmitted pilot tone [8]. For such high order QAM constellations, pilot tones may actually be indispensable for the phase recovery.

There are however a number of drawbacks with self-homodyne systems. The polarization needs to be tracked before the receiver to be able to separate the pilot tone and the data signal with a polarization beam splitter before the 90° optical hybrid. Optical polarization tracking can be achieved by using LiNbO$_3$-based polarization controllers [13]. Alternatively, a silica-based DQPSK receiver was recently demonstrated [14] and a similar technology could be used for the polarization tracking in a self-homodyne system as well.

Another drawback of self-homodyne systems is that the pilot tone becomes affected by amplified spontaneous emission (ASE) noise from optical amplifiers. However, it has been shown that with narrow filtering of the pilot tone in the receiver and optimization of the power ratio between the pilot tone and the signal, the performance penalty compared to an intradyne system can be reduced and in theory be close to zero [15].

A third drawback is that conventional PDM cannot be used due to the presence of the pilot tones. This reduces the spectral efficiency in a self-homodyne system by 50% compared to an intradyne system. However, we have demonstrated the *interleaved polarization division multiplexing* (IPDM) scheme, which enabled us to increase the spectral efficiency of self-homodyne systems [16]. Using 10 Gbaud QPSK, we have reported experimental results for the performance of IPDM back-to-back and after transmission (200 km), both in the linear and nonlinear regime for different spectral efficiencies. We have also compared with 10 Gbaud PDM-QPSK using intradyne detection. The IPDM concept operated as expected, and a 33% increase in spectral efficiency was achieved compared to a self-homodyne system with data in a single polarization. It was evident, however, that the performance was limited by the filters used in the experiment.

In this paper, we extend the experimental work by performing numerical simulations to investigate the impact of filtering on IPDM. In particular, we look at the impact of different shapes and bandwidths of the pilot tone filter. It is shown that the performance of the IPDM system is highly dependent on the filtering and that very good performance can be obtained if a combination of data prefiltering, narrow optical band-pass filtering before the receiver, and narrow pilot-tone filtering is used. As described in [15], a further reduction of the optical signal-to-noise ratio (OSNR) requirements can be expected if the power ratio between the pilot tone and the signal is optimized depending on the bandwidth of the pilot tone filter. We also compare with simulation results for an intradyne system using PDM.

The main motivation for our work on self-homodyne systems is to investigate the performance of coherent systems with significantly reduced (or even eliminated) need for DSP in the receiver. We also believe that future fiber-optical systems using high order QAM formats may benefit from the transmission of pilot tones and that the IPDM scheme, or some variant thereof, could be useful in this context.

The paper is organized as follows: In Section II, the IPDM scheme is described. Sections III and IV present the experiment and the experimental results, respectively. Section V presents the numerical simulations, and the results are discussed in Section VI. Finally, in Section VII, we present our conclusions.

II. INTERLEAVED POLARIZATION DIVISION MULTIPLEXING

We first review the IPDM concept. Fig. 1a shows the spectrum of a WDM signal using PDM and intradyne detection. For each wavelength, data can be transmitted in
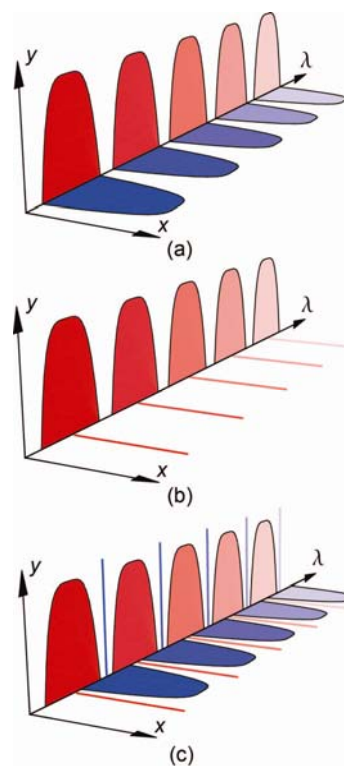

Fig. 1. (a) Spectra of a conventional WDM system using PDM and intradyne detection in the receiver. (b) Spectra of a self-homodyne WDM system using a single polarization state to transmit data. (c) Spectra of a self-homodyne system using IPDM.

both the x- and the y-polarization but the co-propagating pilot tones in a self-homodyne system do not permit the use of such a spectrum. This can be understood by looking at Fig. 1b which shows a typical signal spectrum in a self-homodyne WDM system: only one of the two polarization states is used to transmit data and thus the spectral efficiency is reduced by a factor of two compared to the system illustrated by Fig. 1a.

However, by using IPDM and placing the signals as in Fig. 1c, it is possible to enhance the spectral efficiency compared to case 1b. The channel spacing is the same in both the x- and the y-polarization, but a relative wavelength shift is made that allows the pilot tones to fit in between the tributary data spectra.

Considering the fact that the pilot tones require very narrow bandwidth, it should be expected that with optimized filtering, the difference in spectral efficiency between a self-homodyne system and an intradyne system is reduced significantly. There are several important filtering issues to consider. First, it is important to minimize any distortion of the pilot tone. Crosstalk from neighboring co-polarized data spectra can be reduced by including a narrow filter in the pilot tone branch in the receiver. This filter should be as narrow as possible and have a fast roll-off. Furthermore, the side-lobes of the data spectra can be suppressed by prefiltering in the transmitter before combining the different channels. Another important issue is the impact of the pilot tones surrounding each data spectrum. Proper optical filtering before the receiver and/or electrical filtering after photodetection is important to minimize the distortion from these tones.
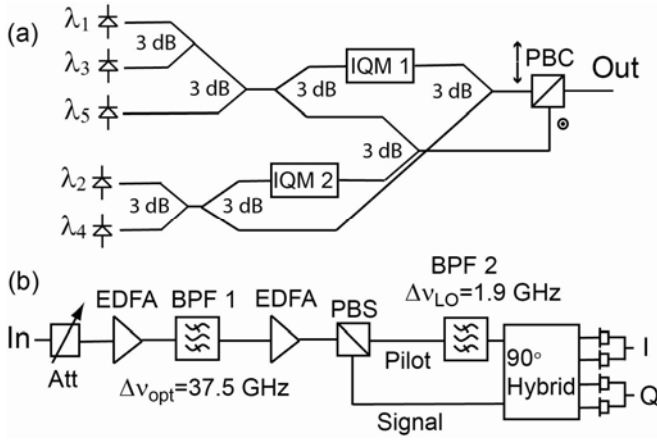
Fig. 2. Experimental setup for the IPDM system. (a) The transmitter with five different channels, and (b) The receiver for the center channel (λ_3).
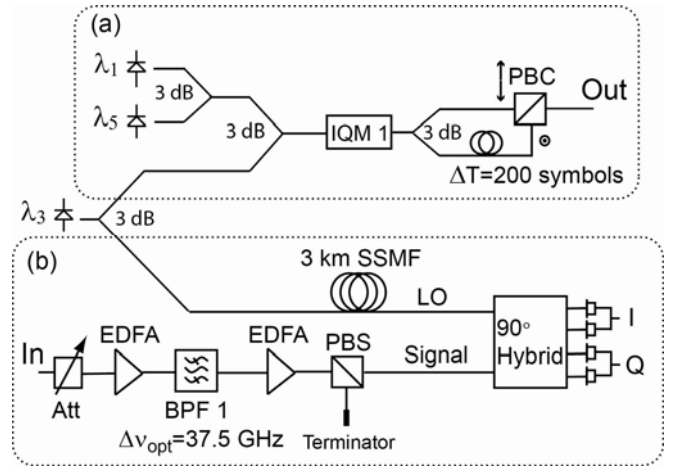

Fig. 3. Experimental setup for the intradyne system. (a) The transmitter with three different channels, and (b) The receiver for the center channel (λ_3).

A system such as the one shown in Fig. 1c requires that the polarization states of the channels are aligned when they enter the transmission line. Furthermore, it requires a new solution for add/drop multiplexing. However, the intention of this work is to investigate the performance limits of systems using IPDM.

III. EXPERIMENTAL SETUP

A. IPDM setup

Fig. 2a shows the transmitter for the self-homodyne system using IPDM. Five channels were used, three (odd channel numbers) with data in the x-polarization and two (even channel numbers) with data in the y-polarization. Two IQ-modulators (IQM 1 and IQM 2) were used, one for each polarization state, and the signals and the pilot tones were combined at the transmitter output by a polarization beam-combiner (PBC), which ensured orthogonal polarizations between the odd and the even channels and between the pilot tones and the corresponding data spectra. Polarization controllers were used in the setup to adjust the polarization state when necessary. The power ratio between the pilot tones and the signals was set to 1 for all channels. 10 Gbaud NRZ-QPSK signals were generated by applying independent $2^{10}-1$ PRBS signals to the modulators. The spectral efficiency was varied between 1.3 bit/(s Hz) and 2.3 bit/(s Hz) by changing the channel spacing from 15 GHz to 8.75 GHz.

The receiver is shown in Fig. 2b. First, a variable attenuator (Att) and an EDFA were used to adjust the OSNR and the input power, and a band-pass filter (BPF 1) with full width half maximum (FWHM) bandwidth of 37.5 GHz selected the center channel. This filter bandwidth is far from optimal for this experiment as it gives insufficient suppression of the pilot tones in the same polarization as the center data channel, particularly with narrow channel spacing.

A polarization beam-splitter (PBS) separated the signal and the pilot tone. The pilot tone passed a Fabry-Perot filter (BPF 2) with 1.9 GHz FWHM bandwidth and was mixed with the signal in a 90° optical hybrid to generate balanced I and Q signals. After photodetection, the photocurrents were sampled with a real-time sampling oscilloscope at 50 GSample/s and

filtered (7 GHz) with an ideal lowpass filter to suppress the beating between the pilot tone of the center channel with the pilot tones of the even channels.

Real-time BER measurements could not be performed due to a relative phase drift between the pilot tone and the signal induced by temperature fluctuations in their different optical paths when they are separated. This phase drift rotates the received constellation randomly in the complex plane. It is very slowly varying compared to the symbol rate and does not affect the BER during a measurement burst with the oscilloscope. To perform real-time measurements, integrated components such as in [9-12] are needed.

B. Intradyne setup

Fig. 3a shows the transmitter used in the intradyne measurements. IQM 1 was used to generate 10 Gbaud NRZ-QPSK. PDM was emulated by splitting the signal equally and recombining it with a relative delay of about 200 symbols. In the WDM case, 3x2 channels (3 wavelengths with data in both polarization states) were used since in the intradyne case the important linear crosstalk comes from the channels at the two neighboring wavelengths. Note that the intradyne system has twice the data rate per wavelength compared to the self-homodyne system. However, since the focus of this work was to compare spectral efficiencies, we believe it is appropriate to use the same symbol rate for both systems as the penalties induced by bandwidth limitations of components will be the same for both cases. The spectral efficiency was varied from 1.6 bit/(s Hz) to 3.2 bit/(s Hz) by varying the channel spacing from 25 GHz to 12.5 GHz.

Fig. 3b shows the intradyne receiver. The same laser was used as both signal source and LO. Its linewidth was 0.5 MHz. 3 km of standard single-mode fiber (SSMF) was added to the LO path for phase decorrelation. The sampling and the low-pass filtering were the same as for the self-homodyne system, and phase estimation was performed with the Viterbi-Viterbi algorithm [17]. Since the 90° optical hybrid did not have polarization diversity, the BER was measured for each polarization separately and then averaged. A fiber terminator was connected to the unused PBS output.
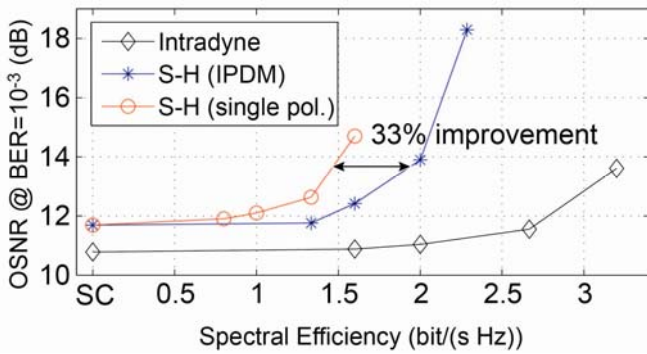
Fig. 4. Required OSNR to obtain a back-to-back BER of 10^{-3} for the system using IPDM, a self-homodyne system with data in a single polarization, and an intradyne system using polarization division multiplexing. SC = single channel. S-H = self-homodyne.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The OSNR is defined as

$$\text{OSNR} = \frac{1}{2S_{\text{ASE}}} \frac{P_{\text{sig}} + P_{\text{pilot}}}{\Delta\nu_{0.1\text{nm}}}, \tag{1}$$

where P_{sig} is the combined signal power in both polarizations, P_{pilot} is the power of the pilot tone, S_{ASE} is the power spectral density of the ASE noise, and $\Delta\nu_{0.1\text{nm}}$ is the reference noise bandwidth in the OSNR measurement. The same expression is used to measure the OSNR for both the self-homodyne and the intradyne system. In the latter case, P_{pilot} is zero.

Fig. 4 shows the required OSNR (0.1 nm reference bandwidth) to obtain a back-to-back BER of 10^{-3} for the self-homodyne system using IPDM, a self-homodyne system using a single polarization (only the odd channels were used) to transmit data, and the intradyne system using PDM, respectively. For the IPDM system, a spectral efficiency of 1.3 bit/(s Hz), achieved by having a channel spacing of 30 GHz in each polarization, gives about the same performance as the single channel case. Spectral efficiencies of 1.6 bit/(s Hz), 2.0 bit/(s Hz) and 2.3 bit/(s Hz) give penalties of 0.7 dB, 2.2 dB and 6.6 dB respectively, at a BER of 10^{-3}. The BER was also measured for two cases (1.6 bit/(s Hz) and 2.0 bit/(s Hz)) after 200 km (4x50 km) transmission with −9 dBm input power (signal and pilot tone combined) per channel to each fiber span. Performance was the same as back-to-back, which is expected for moderately long links when operating in the linear regime. Chromatic dispersion was compensated with dispersion compensating fiber after each SSMF span.

The system using intradyne detection was much more robust to narrow channel spacing. A spectral efficiency of 3.2 bit/(s Hz) could be achieved with 3 dB OSNR penalty compared to the single channel case. As a comparison, the self-homodyne system with data in a single polarization gets a 3 dB penalty when going from the single channel case to the case with a spectral efficiency of 1.6 bit/(s Hz). This is expected since the channel spacing is the same as in the intradyne system with 3.2 bit/(s Hz).

Fig. 4 also shows that the intradyne system requires about 1 dB lower OSNR than the self-homodyne system in the single channel case. To explain this, we see in (1) that the self-homodyne system gets a 3 dB OSNR increase relative to the intradyne system due to the inclusion of the pilot tone (assuming $P_{\text{sig}} = P_{\text{pilot}}$). In the absence of any pilot tone filtering, the ASE noise on the pilot tone adds an additional 3 dB penalty. In our case, the 1.9 GHz filter improves the performance with about 2 dB [15], and since the intradyne system gets a 3 dB OSNR increase when PDM is used (P_{sig} is doubled), the resulting difference is 1 dB.

Finally, we note that for an OSNR penalty of 2 dB compared to the single channel case, the IPDM scheme increases the spectral efficiency with 33% compared to the case in which only one polarization is used to transmit data. The main reason for the rapid performance degradation at high spectral efficiencies is probably that the 1.9 GHz pilot tone filter has a quite slow roll-off which gives insufficient suppression of the power from the data spectra of the even channels. We anticipate that the use of a more narrow pilot tone filter with faster roll-off would improve the performance and make it possible to increase the spectral efficiency. Another reason for the degradation is the increased overlap between the pilot tone of the center channel and the tails of the data spectra of the even channels. This can be avoided by prefiltering of the data in the transmitter. To investigate these issues further, we have performed numerical simulations of the system.

V. NUMERICAL SIMULATIONS

To gain more understanding of the experimental results and to investigate the performance limits of the IPDM system we have performed Monte Carlo simulations. As in the experiment, the WDM system consisted of five 10 Gbaud QPSK channels. Three of these carried data in the x-polarization and two in the y-polarization. For each channel, two independent binary sequences with 2^{15} symbols of random data were used for I and Q modulation respectively.

A. Prefiltering in the transmitter

Prefiltering and pulse shaping were performed by using a raised-cosine filter [18]. The prefiltering is important to achieve high spectral efficiency in an IPDM system, since data spectra with unsuppressed side-lobes affect the pilot tones. The transfer function of the filter is

$$T(\nu) = \begin{cases} \nu_1 = \dfrac{1-\alpha}{2T}, \quad \nu_2 = \dfrac{1+\alpha}{2T} \\[2mm] 1, \quad |\nu| < \nu_1 \\[2mm] \dfrac{1}{2}\left[1 + \cos\left(\dfrac{\pi T}{\alpha}\big[|\nu| - \nu_1\big]\right)\right], \quad \nu_1 < |\nu| < \nu_2 \\[2mm] 0, \quad \text{otherwise} \end{cases} \tag{2}$$

where v is the frequency, T is the inverse symbol rate and α is the roll-off parameter. A FWHM bandwidth of 7.0 GHz was used for the raised-cosine filter and α was set to 0.7. In a real system, prefiltering can be achieved by filtering the driving signals to the modulators [19]. In the experiment, the only filtering in the transmitter was due to the inherent bandwidth limitations of the modulators and the electronics. As it was shown that changes of the prefiltering bandwidth had only a small impact on the performance it was kept constant in all the simulations.

B. Filtering before the receiver

To obtain good performance in a system using IPDM, it is important to have high suppression of the power of the two neighboring pilot tones in the same polarization as the data spectrum that is being demodulated. Otherwise there will be a strong beating between these and the pilot tone used for demodulation of the data. The best way to handle this issue is to use a narrow optical band-pass filter before the receiver (BPF 1 in Fig. 2) with fast roll-off, although it is also possible to use a sharp electrical notch filter that removes the beating term. In the experiment a sharp electrical filter was used after detection due to the lack of a suitable optical filter. In the simulations we used a 4th order super-Gaussian filter before the receiver, due to the sharp cut-off characteristics of these filters. Its transfer function is given by

$$T(v) = \exp\left[-\left(\frac{v}{v_0}\right)^{2m}\right], \qquad (3)$$

where m=4 for a 4th order filter and v_0 is the 1/e bandwidth. The FWHM bandwidth is related to the 1/e bandwidth as

$$v_{FWHM} = 2v_0(\log_2 2)^{1/2m} . \qquad (4)$$

The bandwidth was optimized to minimize the BER for each case and was in the range 10-14 GHz.

C. The pilot tone filter and the electrical filter

The pilot tone filter (BPF 2 in Fig. 2) is important because it has a big impact on the quality of the phase reference, which is crucial in a coherent system. This filter should be narrow and ideally have a fast roll-off to reject power from the neighboring data spectra.

In the simulations we used different channel spacings, filter shapes, and filter bandwidths to investigate the performance limits. We used both a square-shaped pilot tone filter and a Fabry-Perot filter, like the one used in the experiment. The bandwidths were 2.0 GHz and 0.1 GHz. Even though the latter bandwidth is very narrow, such filters are available commercially. For practical implementation, a feedback loop is required that aligns the center frequency of the filter with the carrier frequency of the channel to detect. The transfer function of the Fabry-Perot filter is given by
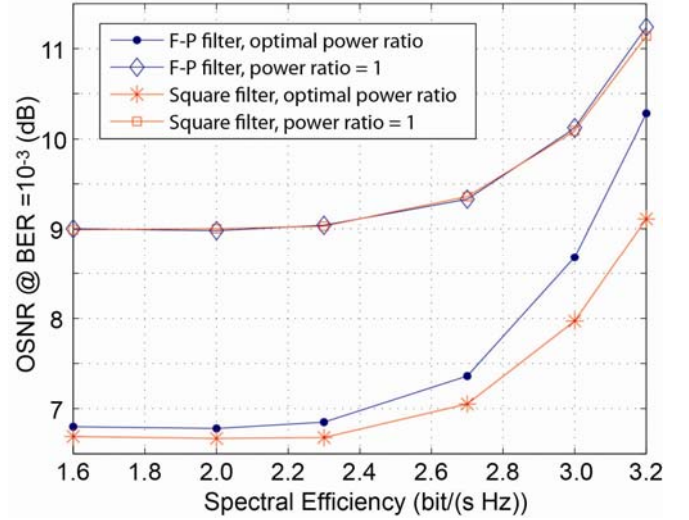

Fig. 5. Comparison between two different pilot tone filters and between $P_{pilot}/P_{sig}=1$ and optimized power ratio between the pilot tone and the signal. The bandwidth of the filters was 0.1 GHz. F-P = Fabry-Perot.

$$T(v) = \frac{1}{\sqrt{1 + \left(\frac{2F}{\pi}\right)^2 \sin\left(\frac{\pi v}{v_{FSR}}\right)^2}} , \qquad (5)$$

where the free spectral range is defined as $v_{FSR} = v_{FWHM} F$. Its Lorentzian shape has a quite slow roll-off which permits more power from the neighboring data spectra to pass compared to the square filter. The finesse F was set to 400 in the simulations.

The electrical filter was a 5th order Bessel filter with a FWHM bandwidth of 7.0 GHz in all simulations. Its transfer function is given by

$$T(v) = \frac{\theta_5(0)}{\theta_5(v/v_0)} , \qquad (6)$$

where θ_5 is the fifth order reverse Bessel polynomial and v_0 is chosen to give the desired cut-off frequency. If a narrow band-pass filter is used before the receiver, the electrical filter does not have a big impact on performance.

D. Power ratio optimization

To investigate the performance limits of the IPDM system, we optimized the power ratio between the pilot tone and the signal according to [15], in which it was derived that if the pilot tone filter has the bandwidth Δv_{pilot} and the electrical filter has the bandwidth Δf, the optimal power ratio is given by

$$\left(\frac{P_{pilot}}{P_{sig}}\right)_{opt} = \sqrt{\frac{\Delta v_{pilot}}{\Delta f}} . \qquad (7)$$

Note that for a narrow pilot tone filter bandwidth, the pilot tone power can be decreased substantially which reduces the problems with the mentioned beating between pilot tones. On
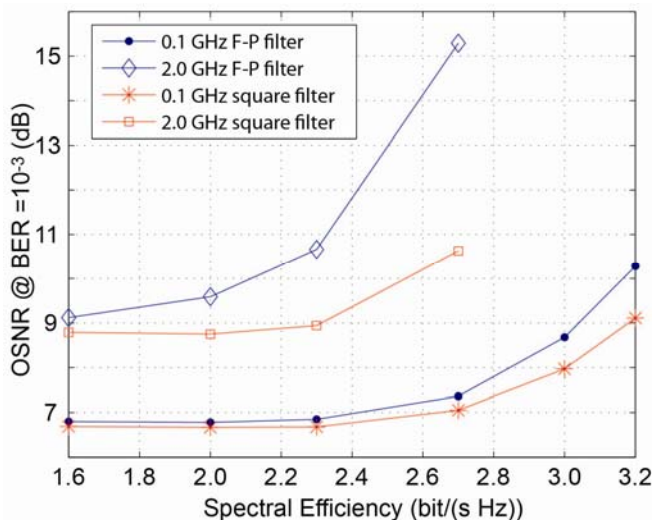
Fig. 6. Comparison between pilot filter bandwidths of 0.1 GHz and 2.0 GHz for the Fabry-Perot (F-P) filter and the square filter. An optimized power ratio between the signal and the pilot tone is used.
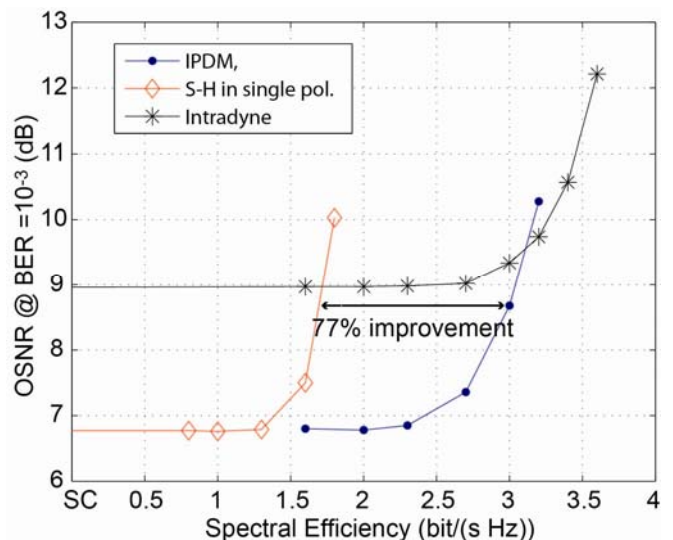

Fig. 7. Comparison between three different systems: A system using IPDM, a self-homodyne system using a single polarization to transmit data and a system using PDM and intradyne detection. The optimal power ratio between the pilot tone and the signal were used for both self-homodyne cases. SC = single channel, and S-H = self-homodyne.

the other hand, when the power of the pilot becomes small, the sensitivity to interference with data spectra increases.

E. Comparison with a system using intradyne detection

Finally, we compared the performance of the optimized IPDM system with a system using conventional PDM and intradyne detection. As in the experiment, three different wavelengths were used. Laser phase noise was neglected in the simulations which probably makes the performance slightly better compared to what could be achieved in a practical case. Similar raised-cosine pulses were used as in the simulations of the self-homodyne system. To make the comparison between the systems fair, super-Gaussian filtering was used also in the intradyne case and the bandwidths were optimized for each value of the channel spacing (10−14 GHz). For an intradyne system with balanced detection, this filtering is not as important as in a self-homodyne system, since intradyne systems are quite insensitive to spontaneous-spontaneous beat-noise [15] and since there are no co-transmitted pilot tones. Finally, the electrical filter was identical as for the self-homodyne system.

VI. SIMULATION RESULTS AND DISCUSSION

In all the presented results, at least 500 bit errors were counted for each point on the curves. Fig. 5 shows the OSNR required to obtain a BER of 10^{-3} for an IPDM system for a 0.1 GHz square-shaped pilot tone filter and a 0.1 GHz Fabry-Perot filter. Both unity power ratio and an optimized power ratio (0.12 for a 0.1 GHz filter) between the pilot tone and the signal were used. For both filters, there is slightly more than 2 dB reduction in the required OSNR for the single channel case when the power ratio is optimized. This agrees well with theory [15]. For the given filter bandwidth and a unity power ratio between the signal and the pilot tone the performance difference between the two filters is quite small for the simulated spectral efficiencies. This is because when the pilot tone power is strong, it gets less sensitive to disturbances from

the neighboring data spectra. On the other hand, when the power ratio is optimized the square filter performs better than the Fabry-Perot filter, especially at higher spectral efficiencies. The explanation is that when the channels are more densely packed, it gets increasingly important to have a fast roll-off of the filter. This conclusion is supported by Fig. 6, in which the performance with a pilot filter bandwidth of 0.1 GHz is compared to the case with a 2.0 GHz filter. The power ratio was optimized and equal to 0.53 for the 2.0 GHz filter. For the Fabry-Perot filter with bandwidth of 2.0 GHz, it is not possible to achieve higher spectral efficiency than 2.7 bit/(s Hz), and at this spectral efficiency we observe roughly 8 dB penalty compared to when the bandwidth is 0.1 GHz. The square shaped filter gives better performance, due to its fast roll-off. The conclusion is that it is crucial to have a narrow filter bandwidth and that the shape of the filter has a bigger influence for large bandwidths.

Fig. 7 shows a comparison between the system using IPDM, the self-homodyne system using only a single polarization to transmit information, and the intradyne system with PDM. The intradyne system has the highest spectral efficiency, but with proper filtering, comparable performance can be achieved by the IPDM system. We now observe a 77% increase in spectral efficiency when comparing with the self-homodyne system that uses only a single polarization. The IPDM curve starts at a spectral efficiency of 1.6 bit/(s Hz) since this gives similar performance as the single channel case with self-homodyne detection.

When comparing the single channel cases, Fig. 7 shows that there is a 2.2 dB reduction in the required OSNR for the self-homodyne system compared to the intradyne system with PDM. To understand this, we note that for $P_{sig} = P_{pilot}$ and a narrow pilot tone filter bandwidth of 0.1 GHz, the OSNR requirements should be approximately the same for the two systems [15]. However, the optimization of the power ratio

reduces the OSNR requirement for the self-homodyne system with 2.2 dB in this case.

When comparing the experimental results with the simulations, we first note that the single channel case with PDM-QPSK and intradyne detection has approximately 2 dB higher sensitivity in the simulations. This difference is reasonable taking into account that the components used in experiments are non-ideal. For the self-homodyne system, the difference in single channel performance between simulation and experiment is close to 5 dB. The reasons for this are the optimized power ratio between the pilot tone and the signal, and the narrower filter that was used in the simulations.

In summary, the simulation results show that good performance can be achieved with a system using IPDM and self-homodyne detection, and that optimized filtering is crucial to achieve good performance.

VII. CONCLUSIONS

By performing both experiments and numerical simulations, we have investigated the performance of a self-homodyne WDM system using QPSK and interleaved polarization division multiplexing. The results show that the scheme can increase the spectral efficiency of self-homodyne systems and that very good performance can be achieved by using optical filtering before the receiver and narrow pilot tone filtering.

In the experiment, a 33% increase in the spectral efficiency was obtained compared to a self-homodyne system using a single polarization to transmit data. The simulations showed the benefits of better filtering. In particular, by using a 0.1 GHz Fabry-Perot pilot tone filter and optimization of the power ratio between the pilot tone and the signal, a 77% increase in spectral efficiency was achieved.

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