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Performance analysis of coherently detected orthogonal wavelength division multiplexing scheme

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ABSTRACT

In this paper, a highly spectrally efficient scheme orthogonal wavelength division multiplexing with coherent detection (Co-OWDM) is analyzed. We study the effect of channel spacing on inter-channel crosstalk induced power penalty and on decision threshold Q-factor; effect of number of channels on Q-factor is also discussed. Results obtained with coherent detection are compared with direct detection technique. We also analyzed Co-OWDM with quadrature phase shift keying (QPSK) technique, passive micro-optics based 90° optic is used for coherent detection in this technique. QPSK based Co-OWDM system performance is analyzed in terms of bit error rate (BER) and quality factor.

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1. Introduction

The revolution in high bandwidth applications and the explosive growth of the internet have created capacity demands that exceed traditional TDM limits. Technologies such as wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) have been developed to meet exponentially growing bandwidth demands. In addition, high spectral efficiency (SE) can effectively increase the aggregate capacity without resorting to expanding the bandwidth of optical amplifiers. There are two ways to increase SE in optical transmission for which coherent detection is ideally suited. One way is to use advanced modulation formats so that each symbol transmits multiple bits of information. The other way is to pack WDM channels closer together [1]. The price paid in the latter option is increased crosstalk. In dense DWDM networks, optical orthogonal techniques are required to enhance the receiver performance. Orthogonal wavelength division multiplexing (OWDM) is another high spectral efficient DWDM scheme in which channels are allowed to overlap without interfering each other [2]. This condition can be achieved only when channel spacing is precisely set equal to the symbol rate; in this case linear crosstalk induced from adjacent channel presents a deep power notch at the central frequency of the channel under study. Inter-channel crosstalk can be completely eliminated if square pulses are used as transmission signals and samples are taken at center of the pulses at the receiver. Coherent detection can further improve the receiver sensitivity compared with the direct detection with an advantage of ultra narrow optical filtering [3].

2. Performance analysis of co-OWDM system

Initially we analyze single polarization binary amplitude-shift-keyed (ASK) transmission format with co-polarized DWDM channels. We considered coherent detection of one DWDM channel (channel i) with optical spectrum envelope $S_i(\omega)$ in the presence of adjacent channel (linear crosstalk) $S_n(\omega)$ with frequency separation Δf. For homodyne detection local oscillator (LO) $S_{LO}(\omega)$ having circular frequency same as frequency of channel i is used [4,5]. Channel $S_i(\omega)$ is centered at angular frequency ω, and the channel n is centered at angular frequency

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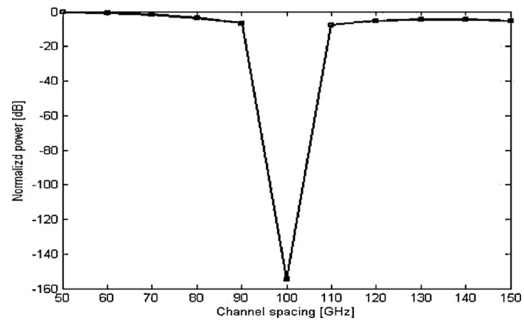

Fig. 1. Interfered noise power spectrum of Co-OWDM.

$\omega_n = \omega_i + 2\pi \cdot \Delta f$. At the receiver end, photo-detected intensity $\boldsymbol{I}_{det}$ is proportional to the power spectrum at the photo detector and can be written as:

$$\boldsymbol{I}_{\text{det}} \sim |S_i(\omega) + S_n(\omega) + S_{LO}(\omega)|^2 \sim \underset{(A)}{|S_i(\omega)|^2} + \underset{(B)}{|S_n(\omega)|^2} + \underset{(C)}{|S_{LO}(\omega)|^2} + \underset{(D)}{2|S_i(\omega)||S_n(\omega)|} + \underset{(E)}{2|S_i(\omega)||S_{LO}(\omega)|} + \underset{(F)}{2|S_n(\omega)||S_{Lo}(\omega)|} \quad (1)$$

Here E contains the message information, A, B and C are the noise signals centered at the frequencies of channels i, n and local oscillator respectively. D and F are the interfered noises of channels $i - LO$ and channels $i - n$ respectively. In case of homodyne detection A, B and C can be eliminated by using appropriate electrical filter and the information signal is given by:

$$F^{-1}\{S_i(\omega)S_{LO}(\omega)\} = s_i(t) * s_{LO}(t) = \tau \ \exp j(\phi s + \phi LO) \quad (2)$$

And noises D&F is given as

$$\begin{aligned} |S_n(\omega)||S_{LO}(\omega)| &= \int_{-\infty}^{\infty} p(t) \exp j[(\omega_o + 2 \cdot \pi \cdot \Delta f - \omega_{LO})t + (\phi_n + \phi_{LO})]dt \\ &= \exp \quad j(\phi_n + \phi_{LO})\text{sinc}(\Delta f \cdot \tau) \\ \text{and} & \\ |S_i(\omega)||S_n(\omega)| &= \tau \exp j(\phi_i + \phi_n) \exp(j \cdot \pi \cdot \Delta f \cdot \tau)\, \text{sinc}(\Delta f \cdot \tau) \end{aligned} \quad (3)$$

The noise power spectrum shown in Fig. 1 shows deep power notch at $\Delta f = 100$ GHz which is the channel spacing corresponding to 10-ps transform-limited square time pulses used here.

Power penalty is calculated as [6]

$$PP_{dB} = -10 \ \log \frac{(P_1' - P_0')}{(P_1 - P_0)} \quad (4)$$

where P_1' and P_0' are the power received during 1 bit and 0 bit respectively in the presence of impairments and P_1 and P_0 are the power received during 1 bit and 0 bit without any impairment. In our case (in normalized form)

$$P_1' = \exp j(\phi_s + \phi_{LO}) + \exp j(\phi_n + \phi_{LO})\text{sinc}(\Delta f \cdot \tau) + \exp j(\phi_i + \phi_n) + \exp(j \cdot \pi \cdot \Delta f \cdot \tau)\, \text{sinc}(\Delta f \cdot \tau)$$

$$P_0' = 0, \quad P_1 = \exp j(\phi_s + \phi_{LO}) \quad \text{and} \quad P_0 = 0$$

$$PP_{dB} = -10 \log_{10}(1 + \exp j(\phi_n - \phi_s)\text{sinc}(\Delta f \cdot \tau) + \exp j(\phi_n - \phi_{LO}) \exp(j \cdot \pi \cdot \Delta f \cdot \tau)\text{sinc}(\Delta f \cdot \tau))$$

Assuming the worst case, that is taking the phase of both noises equal to -1.

$$PP_{dB} = -10 \ \log_{10}(1 - \text{sinc}(\Delta f \cdot \tau) - \exp(j \cdot \pi \cdot \Delta f \cdot \tau)\text{sinc}(\Delta f \cdot \tau)) \quad (5)$$

Effect of channel spacing on Q-factor in Co-OWDM system can be analyzed by setting Q-factor approximately equal to 14 dB in the absence of adjacent channels. The decision-threshold Q-factor versus channel spacing is shown in Fig. 2, when the channel spacing is much tighter than the symbol rate, a large penalty is incurred. Increasing the channel spacing even further actually increases the penalty, after certain channel spacing the channels are spaced enough so that the spectral overlap is diminished and the Q-factor increase.

Fig. 3 shows that effect of interchannel crosstalk is zero when channel spacing is equal to symbol rate and effect of channel spacing on interchannel crosstalk is more severe in the case of Co-OWDM than OWDM with direct detection.

Now we increased number of channels from 2 to 3 and take worst condition when signal of channel 2 is affected by both signals of channel 1 and channel 3 and coherently detected, in this case photo-detected intensity $\boldsymbol{I}_{det}$ is given by:

$$\begin{aligned} \boldsymbol{I}_{\text{det}} \sim & |S_1(\omega) + S_2(\omega) + S_3(\omega) + S(\omega) + S_{LO}(\omega)|^2 \sim |S_1(\omega)|^2 + |S_2(\omega)|^2 + |S_3(\omega)|^2 + |S_{LO}(\omega)|^2 + 2|S_1(\omega)| + |S_2(\omega)| + 2|S_1(\omega)||S_{LO}(\omega)| \\ & + 2|S_2(\omega)| + |S_{LO}(\omega)| + 2|S_3(\omega)| + |S_{LO}(\omega)| + 2|S_3(\omega)||S_1(\omega)| \cdots + 2|S_3(\omega)||S_2(\omega)| + 2|S_3(\omega)||S_2(\omega)| \end{aligned} \quad (6)$$

Here $S_1(\omega)$, $S_2(\omega)$, $S_3(\omega)$ and $S_{LO}(\omega)$ are Fourier transform of time domain electric field of optical signal $s_1(t)$ of channel 1, $s_2(t)$ of channel 2, $s_3(t)$ of channel 3 and $s_{LO}(t)$ of local oscillator respectively. First four terms are not our interest and can be filtered out by passing the

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