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Chromatic dispersion monitoring technique using optical asynchronous sampling and double sideband filtering

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ABSTRACT

This paper introduces a new chromatic dispersion monitoring technique using optical asynchronous sampling and double sideband filtering. We present simulation results that relate chromatic dispersion with the ratio between the maximum amplitude of the signal and the average optical output power, yielding in a method which is power transparent. We also show theoretical investigation and theoretical results that prove the approach used in this paper.

1. Introduction

Chromatic dispersion is well known as one of the most limiting impairments in optical communications. Prior work in the field of chromatic dispersion monitoring, implemented various schemes, including asynchronous delay tap sampling [1,2], RF tone measurement [3,4], self phase modulation (SPM), four wave mixing (FWM) and cross phase modulation (XPM) [5–7], polarization scrambling [8], asynchronous chirp [9], two photon absorption (TPA) with semiconductor micro-cavity [10], and so on.

The well known RF tone measurement techniques cannot isolate chromatic dispersion, because are known to be sensitive to a variety of distortion effects including PMD [11]. Although,is a technique with moderate dynamic range, cost, and acquisition time and also suitable to implement [12]. Monitoring chromatic dispersion by nonlinear effects (TPA, FWM, SPM, XPM) avoids high speed electrical domain signal processing, but requires normally high power, due to the low efficiency of the nonlinear process [5–7,10].

The technique here presented, collects samples of data at asynchronous intervals, and determines the maximum amplitude of the optical signal in an appropriate time window. Fig. 1 shows the simulation setup of the monitoring technique. The processor samples the signal asynchronously and determines the maximum amplitude of it. Then it divides this value by the average power calculated by the optical power meter of Fig. 1, yielding in a ratio (known in telecommunications engineering to be the Peak to Average Power Ratio (PAPR)) transparent to the average power of the laser. The optical filter selects the two sidebands of the signal, rejecting all the others. The chromatic dispersion influence of the two sidebands, in the phase of the optical field, is isolated from the chromatic dispersion influence of the other sidebands. Without the filter, the phase shift produced by the chromatic dispersion in the other sidebands, will influence the phase and also the intensity of the optical field, in a manner, that the optical peak power versus chromatic dispersion is no longer a monotonic function. This implies that the optical filter is crucial for this method. The mach-zhender interferometer with $\tau = 1/(2f_p)$, has the effect of reducing the optical power when there is no dispersion. The interferometer shifts the phase between the optical carrier and the two sidebands $+\pi/2$ and $-\pi/2$, respectively, so that these two sidebands have a π phase difference, and therefore, they could cancel each other. Chromatic dispersion changes this phase difference, and the PAPR starts to increase when dispersion departs from 0 ps/nm.

This method, relatively to the ones mentioned above, is very simple to implement. Also, by using optical sampling, has fast acquisition time and do not require high power, like the monitoring techniques using nonlinear effects.

Relatively to the RF tone techniques and specifically to the one presented in [13], besides the most obvious differences, which is the fact that we do not measure the RF power, but measure the peak optical power (which is not correlated with the RF power, as stated further in this paper, by the final Eq. (14). This one relates chromatic dispersion with the optical peak power by a sine modulus, instead of a sine square or a cosine square as regular RF tone measurement techniques do), and the fact that the optical domain part of the setup is different, we do not use also an RF filter. This allows to use optical domain processing techniques, to measure the peak optical power, instead of using high speed electrical domain techniques, to measure the RF power. Optical sampling is

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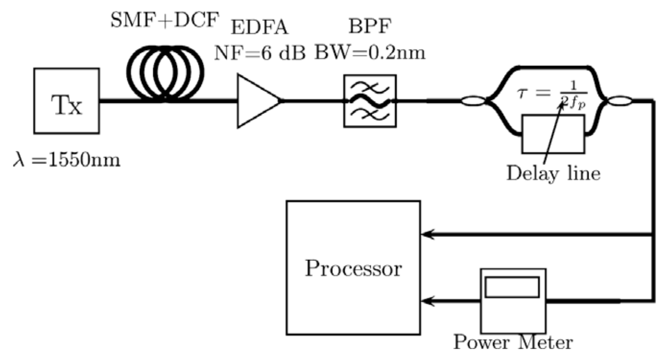

Fig. 1. Simulation setup: BPF – band pass filter, BW – bandwidth, τ – time delay of the intereferometer, EDFA – erbium doped fiber amplifier, SMF – single mode fiber, DCF – dispersion compensating fiber, and NF – noise figure.

faster than electrical sampling. This implies that the acquisition time of this method is shorter than the monitoring technique of [13] or any other technique based in RF pilot tones.

2. Theory

The electric field equation of a sinusoidal input modulation, after passing through a dispersive fiber, an ideal filter and an interferometer is given by (1) [13]:

$$r(t) = \sqrt{P_0}H_1 e^{i\phi_1+2i\pi t f_0}\left(1+1/4\frac{m(H_2+H_3)e^{i(qf_p^2-\phi_1+1/2\phi_2+1/2\phi_3)}}{H_1}\times\frac{\cos(2\pi f_p t+1/2\phi_2-1/2\phi_3)}{H_1}+1/4i\frac{m(H_2-H_3)e^{i(qf_p^2-\phi_1+1/2\phi_2+1/2\phi_3)}}{H_1}\times\frac{\sin(2\pi f_p t+1/2\phi_2-1/2\phi_3)}{H_1}\right)\otimes\mathbb{F}^{-1}\{rect(f_0,f_{BW})\}, \quad (1)$$

where f_p is the frequency of the sinusoid, f_0 is the carrier frequency, P_0 is the average laser launch power, m is the modulation index, $\mathbb{F}^{-1}\{rect(f_0, f_{BW})\}$ is the inverse Fourier transform of an ideal filter centered at f_0, with frequency bandwidth equal to f_{BW} and $\otimes$ is the convolution operator. The H_1, H_2, H_3, ϕ_1, ϕ_2, ϕ_3 and q, parameters are defined as follows:

$$\begin{aligned}
H_1 &= |\cos(\pi\tau f_0)|,\\
H_2 &= |\cos(\pi\tau(f_0+f_p))|,\\
H_3 &= |\cos(\pi\tau(f_0-f_p))|,\\
\phi_1 &= -\pi\tau f_0+\frac{\pi}{2}+\angle\cos(\pi\tau f_0), \quad (2)\\
\phi_2 &= -\pi\tau f_0+\frac{\pi}{2}+\angle\cos(\pi\tau(f_0+f_p))-\pi\tau f_p,\\
\phi_3 &= -\pi\tau f_0+\frac{\pi}{2}+\angle\cos(\pi\tau(f_0-f_p))+\pi\tau f_p,
\end{aligned}$$

$$q = \frac{\pi\lambda_0^2 DL}{c}, \quad (3)$$

where λ_0 is the carrier central wavelength, D is the dispersion parameter, L is the fiber length, $\angle$ is the angle operator and τ is the delay time of the delay line of Fig. 1 which is given by:

$$\tau = \frac{1}{2f_p}. \quad (4)$$

In such conditions we can write:

$$\begin{array}{ll}
H_1 = |\cos(\pi\tau f_0)| & H_2 = |\cos(\pi\tau(f_0+f_p))| \\
H_3 = H_2 & \phi_1 = 2\pi n+\alpha \\
\phi_2 = 2\pi n+\alpha+\frac{\pi}{2} & \phi_3 = 2\pi n+\alpha+\frac{\pi}{2},
\end{array} \quad (5)$$

where α is an arbitrary angle dependent of f_0. The optical power is given by:

$$\begin{aligned}
P_{opt} &= |r(t)|^2 = \mathrm{Re}(r(t))^2+\mathrm{Im}(r(t))^2\\
&= \Big(1/4\sqrt{P_0}mH_2\cos(2\pi t f_0+qf_p^2+\phi_2+2\pi f_p t)\\
&\quad +1/4\sqrt{P_0}mH_3\cos(2\pi t f_0+qf_p^2-2\pi f_p t+\phi_3)\\
&\quad +\sqrt{P_0}H_1\cos(2\pi t f_0+\phi_1)\Big)^2+\Big(1/4\sqrt{P_0}mH_2\sin(2\pi t f_0+qf_p^2\\
&\quad +\phi_2+2\pi f_p t)+1/4\sqrt{P_0}mH_3\sin(2\pi t f_0+qf_p^2-2\pi f_p t+\phi_3)\\
&\quad +\sqrt{P_0}H_1\sin(2\pi t f_0+\phi_1)\Big)^2=\frac{1}{16}P_0(m^2H_2^2+2m^2H_2H_3\cos(\phi_2\\
&\quad +4\pi f_p t-\phi_3)+8mH_1H_2\cos(qf_p^2+\phi_2+2\pi f_p t-\phi_1)+m^2H_3^2\\
&\quad +8mH_3H_1\cos(qf_p^2+\phi_3-2\pi f_p t-\phi_1)+16H_1^2). \quad (6)
\end{aligned}$$

Using (5) into (6) we obtain:

$$\begin{aligned}
P_{opt} &= \frac{1}{16}P_0\Big(H_2^2m^2+2m^2H_2H_3\cos(4\pi f_p t)-8mH_2H_1\sin\left(qf_p^2+2\pi f_p t\right)\\
&\quad +m^2H_3^2-8mH_3H_1\sin\left(qf_p^2-2\pi f_p t\right)+16H_1^2\Big). \quad (7)
\end{aligned}$$

To calculate the maximum amplitude of the signal we must derivate (7) in order to time and equalize it to zero:

$$\begin{aligned}
\frac{dP_{opt}}{dt} &= P_0mH_3H_1\cos\left(qf_p^2-2\pi f_p t\right)f_p\pi-1/2P_0m^2H_3H_2\\
&\quad \times\sin(4\pi f_p t)f_p\pi-P_0H_1mH_2\cos\left(qf_p^2+2\pi f_p t\right)f_p\pi=0. \quad (8)
\end{aligned}$$

Then we must find the solutions that fulfil this requirement. We conclude that the solutions are:

$$t=\begin{cases}(2i+1)/(2f_p) & \text{if, } \begin{array}{l} DL \geqslant 2nD_{Talbot} \\ DL < (2n+1)D_{Talbot}\end{array} \\ (2i+1)/(f_p) & \text{if, } \begin{array}{l} DL \geqslant (2n+1)D_{Talbot} \\ DL < (2n+2)D_{Talbot}\end{array}\end{cases}, \quad (9)$$

where $n = \ldots, -2, -1, 0, 1, 2, \ldots$ and $i = 0, 1, 2, \ldots$.

The product DL is the total accumulated dispersion in the fiber. A more thorough study need to be done, because of the use of asynchronous sampling, but some clues can be found taking into account that:

$$T_s = \frac{1}{\frac{k}{j}f_p} \quad k<j, \quad (10)$$

where T_s is the sampling period. Then the following condition must be met:

$$\frac{k}{j} \geqslant \frac{1}{2m+1}, \quad (11)$$

where m is the ith solution of (8), that represents the solution with highest value in an appropriate time window. D_{Talbot} is defined as [14]:

$$D_{Talbot} = \frac{c}{f_p^2\lambda_0^2}. \quad (12)$$

D_{Talbot} is due to the Talbot effect, which describes the apparent re-emergence of a periodic sequence of pulses, propagating in the dispersive medium.

Substituting the solutions given by (9) into (7), for instance for $i = 1$, leads to (13a) and (13b), which is a novel relationship between the maximum amplitude of the signal and chromatic dispersion:

$$P_{opt}(q) = \frac{1}{16}P_0\Big(m^2H_2^2+16mH_2H_1\sin(qf_p^2)2m^2H_2H_3+m^2H_3^2+16H_1^2\Big), \quad (13a)$$

if $2nD_{Talbot} \leqslant DL < (2n+1)D_{Talbot}$ and: