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Low-cost adaptive directly modulated optical OFDM based on semiconductor optical amplifier

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A B S T R A C T

Low cost optical OFDM has great potential for next generation optical access networks and PONs, due to its high flexibility in bandwidth manipulation, and high spectral efficiency. Here, a low cost optical OFDM is proposed, based on adaptive direct modulation semiconductor optical amplifier. Adaptive current loading techniques for PAPR (peak to average power ratio) reduction are proposed and analyzed. Simulations show that the proposed adaptive techniques enable significant BER improvement.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is one of the promising advanced techniques for high capacity data transmission. Due to the high spectral efficiency and spectrum manipulation capabilities, OFDM is also investigated in optical communication systems, particularly in access networks and PONs (passive optical networks). A major disadvantage of OFDM is its high power peaks, which may limit the total system performance due to nonlinear component, and particularly the electrical-to-optical converter (modulator), as it requires strict linearity together with wide dynamic range in order to preserve the analog shape of the time domain OFDM signal. The main advantage of the adaptive modulation is the low cost (compared with systems with external modulation and coherent detection [1]) and simple way of extending the dynamic range of the optical transmitter. In addition, it minimizes the transmitter power consumption due to the optimization of the optical power amplification [2–6]. The disadvantage of it is the introduction of nonlinear modulation and truncation effect. Yet, it is shown in this paper that it leads to optimizes performance. The use of SOA as an intensity modulator in optical OFDM systems was recently proposed and a proof of concept experimental feasibility study was performed by Tang et al. [2]. In his work, modulation bandwidth and transmission distance limitations over SMF have been analyzed. Here this method is extended to include adaptive operation mode that requires real time digital signal processing (DSP) capabilities. However, the incremental DSP complexity is feasible, as the adaptation rate is in the order of the OFDM symbol rate which is two orders of magnitude slower than the state of the art real time DSP ASICs that are currently being implemented in coherent systems.

More recently, direct modulation in optical OFDM based on DFB lasers has been discussed, which led to orthogonality degradation via chirp effect [7] which can be overcome by direct detection but limited to short distance. For the case of longer links (hundreds of kilometers and above) the orthogonality degradation together with chromatic dispersion cannot be overcome by direct detection and requires coherent detection for following DSP compensation [4]. In this paper, a low cost OFDM system, similar to the one proposed in [2] is designed and analyzed for short distances up to a few tens of km, which is the case in most PONs applications. An inclusive analysis of the impact of SOA as intensity modulator on the transmission performance of optical OFDM signals is presented. The optimum SOA operating conditions are investigated. New techniques for improving system performance are proposed by means of adaptive current loading of the SOA modulator. It is shown that the use of adaptive bias PAPR optimization, adaptive peak-to-peak PAPR optimization, or adaptive clipping PAPR optimization improve the system performance significantly. In general, adaptive optimization of the electronic signal level per OFDM symbol reduces significantly the PAPR effect, leading to significant BER improvement.

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2. The proposed SOA-based optical OFDM system

Fig. 1 illustrates the proposed transmission system. This system includes an OFDM transmitter that contains data mapping, serial to parallel, IFFT, cyclic prefix, parallel to serial and digital to analog converter. In turn, the analog signal directly modulates an SOA, and the optical output propagates through SMF link. On the receive side, an OFDM receiver includes a direct detection photodetector, analog to digital converter, serial to parallel, cyclic prefix removal, FFT, parallel to serial and data mapping.

The input to the IFFT is the complex vector $X = [X_0X_1,\ldots,X_{N-1}]^T$; the vector has length N where N is the size of the IFFT. Each of the elements of X represents the data to be carried on the corresponding subcarrier; for example, X_k represents the data to be carried on the kth subcarrier. Usually QAM modulation is used in OFDM, so each of the elements of X is a complex number representing a particular QAM constellation point.

The output of the IFFT is the complex vector $x = [x_0x_1,\ldots,x_{N-1}]^T$ using the definition of the inverse discrete Fourier transform:

$$x_m = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi km}{N}\right) \quad \text{for } 0 \leqslant m \leqslant N-1 \tag{1}$$

where X_k is the frequency domain digital data, N the number of OFDM tones, k the discrete frequency, and m is the discrete time.

The forward-FFT corresponding to (1) is:

$$X_k = \frac{1}{\sqrt{N}}\sum_{m=0}^{N-1} x_m \exp\left(\frac{-j2\pi km}{N}\right) \quad \text{for } 0 \leqslant k \leqslant N-1 \tag{2}$$

At the receiver the FFT performs a forward transform on the received sampled data $y = [y_0\ y_1\ y_{2\ldots y=N-1}]^T$ for each symbol

$$Y_k = \frac{1}{\sqrt{N}}\sum_{m=0}^{N-1} y_m \exp\left(\frac{-j2\pi km}{N}\right) \quad \text{for } 0 \leqslant k \leqslant N-1 \tag{3}$$

In this system a real baseband signal is generated in the IFFT block. A real valued signal is generated by maintaining the relation $I_{i,k} = I^*_{i,N-k}$ for $k = 0,\ldots,N-1$, where $I^*_{i,N-k}$ is the complex conjugate of $I_{i,N-k}$, N is the IFFT block size, and i is the OFDM information symbol [8–11,17].

2.1. SOA as intensity modulator in OFDM systems

The dynamic rate equation of the SOA is shown in [10] and its final form is presented in Eq. (4). This SOA dynamic model has been used in order to obtain the quantitative analysis of the OFDM system presented in the following sections [10]:

$$\frac{dh(\tau)}{d\tau} = \frac{g_o(\tau)L - h(\tau)}{\tau_c} - \frac{P_{in}(\tau)}{E_{sat}}(e^{h(\tau)} - 1) \tag{4}$$

where $h(\tau) = \int_0^L g(z,\tau)dz$ is the integrated gain at the SOA output of the propagating pulse temporal profile. τ is a time frame moving with the propagating signal that replaces the static time variable t and spatial coordinate z, i.e., $\tau = t - \frac{z}{v_g}$, and g_0 is the small signal gain coefficient given by $g_0(\tau) = \Gamma a_1 N_0\left(\frac{I(\tau)}{I_0} - 1\right)$ where Γ is confinement factor, α_1 is linewidth enhancement factor, N_0 is carrier density at transparency, $I(\tau)$ is current and I_0 is the bias current required for transparency. L is the SOA cavity length, $P_{in}(\tau)$ is the optical input pulse power, τ_c is the carrier recombination lifetime and E_{sat} is the saturation energy. For a given input pulse shape and gain $g_0(\tau)L$, Eq. (4) can be solved to obtain $h(\tau)$.

P_{out} can then be found using:

$$P_{out}(\tau) = P_{in}(\tau)\exp(h(\tau)) \tag{5}$$

The parameters of the SOA that was simulated was adopt from Refs. [1,10–14] are presented in Table 1. The dependence of SOA output optical power on bias current for different CW optical input powers is presented in Fig. 2. In each simulation a constant bias current and a constant optical input power were injected into the SOA. It is shown that the optical output power, and thus gain of the SOA depends strongly on both CW optical input power and bias current. In order to obtain an undistorted optical OFDM signal, the desired curve should have linear line shape. It can be seen in Fig. 2 that the CW optical input power should be set greater than 10 dB m and the bias current should be larger than 100 mA in order to obtain the desired linearity. Under such operating conditions the SOAs are strongly saturated, resulting in significantly reduced effective carrier lifetimes [1] and thus wide SOA bandwidths. On the other hand, as shown in Fig. 2, a large CW optical input power broadens considerably the bias current variation range corresponding to the linear current-gain region, and simultaneously declines the slope of the linear current-gain curve, which declines the modulation extinction ration [2]. Therefore, extensive optimization of the SOA operating conditions together with the OFDM-related parameters such as PAPR and SNR is required.

2.2. OFDM system (with SOA as intensity modulator)

The block diagram in Fig. 1 was modeled and simulated using Matlab software. Tables 2–4 summarize the parameters of the

Table 1
SOA parameters.

Symbol	Definition	Value
Γ	Confinement factor	0.35
a_1	Differential gain	3×10^{-20} m^2
N_0	Carrier density at transparency	1.1×10^{24} m^{-3}
L	SOA cavity length	350 μm
τ_c	Spontaneous carrier lifetime	0.3 ns
λ	Wavelength	1.55 μm
w	Width active region	1.5 μm
d	Depth active region	0.17 mm
α_1	Linewidth enhancement factor	5

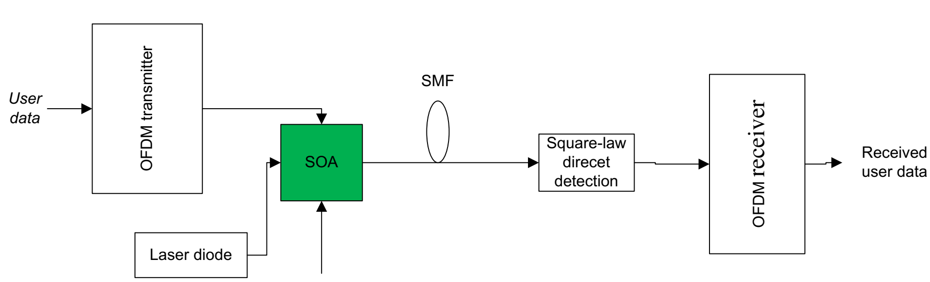

Fig. 1. Transmission system block diagram.