Electrical-to-optical conversion of OFDM 802.11g/a signals by direct current modulation of semiconductor optical amplifiers

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Abstract — We report experimental results showing direct current modulation of a commercial semiconductor optical amplifier (SOA) for electrical to optical conversion of a 64-QAM OFDM analog signal at 54 Mbit/s on 2.5 and 5 GHz carriers. This is believed to be the highest frequency yet experimentally reported for RF signal transmission using a directly modulated semiconductor optical amplifier.

Index Terms — Optical modulation, microwave communication, optical fiber communication, radio-over-fiber (RoF), semiconductor optical amplifiers.

I. INTRODUCTION

The main challenges in radio-over-fiber (RoF) transparent optical links at the physical layer, especially for wireless access networks [1], are the electro-optical (E/O) and the opto-electrical (O/E) conversions at the antenna sites. In order to reduce antenna site complexity, and therefore infrastructure cost, O/E and E/O conversions have to be as low cost and efficient as possible, especially for multiple antenna systems, where the cost of the conversion has to be multiplied by the number of antenna elements. To address this problem, we investigate the possibility of using a single SOA as a dual-purpose device (optical amplifier and modulator) in RoF base stations. The SOA could be used for amplification in the downlink, and as an external modulator for a distributed optical source in the uplink [2]. We focus on the popular IEEE 802.11g/a standard that uses orthogonal frequency division multiplexing (OFDM) signals at a maximum transmission rate of 54 Mbit/s. Results show that it is possible to achieve a quality of service of $10^{-6}$ BER in the uplink at both 2.5 GHz and 5 GHz using a deeply saturated SOA. However, the saturation level imposes a trade-off: deeper saturation gives less distortion (as measured via error vector magnitude) but less received optical power (for a fixed optical input power).

II. THE SOA-BASED BASE STATION

Fig.1 presents the principles of operation of the proposed RoF base station during transmission (a) and reception (b). Optical versions of the RF signals arriving via fiber from the central office to the mobile (downlink) are amplified by the SOA at the base station before photodetection; the photocurrent drives the antenna with the RF downlink signal.

When the antenna is receiving (uplink), the signal coming from the antenna is amplified and summed to a DC current (via a bias tee) to control the injection current of the SOA. In this case a continuous wave (CW) optical signal arriving from the central office will be modulated by current modulation of the SOA.

The ideal characteristics of the SOA for the two functions (amplifier and modulator) are disparate: for amplification, an SOA with a long gain recovery time is preferable [3], while for modulation, especially at high frequencies, an SOA capable of fast recovery of the gain is required. Our SOA has a recovery time around 350 psec.

In this paper we will focus on the uplink; studying the performance of the SOA as a modulator for analog signals such as OFDM signals on 2.5 and 5 GHz carriers in order to investigate the feasibility of the proposed base station and to understand the constraints imposed on the modulation function by the SOA.
III. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup of the analog OFDM signal conversion. The output of a laser diode at 1562 nm, where the SOA amplification gain is maximum, is injected into the SOA (Optospeed 1550MRI) through a variable attenuator and a polarization controller (our SOA is a polarization sensitive amplifier). The SOA bias current is supplied through a bias-tee in order to sum a DC term and an OFDM modulated radio signal, generated by a vector signal generator (Agilent E-4440A). The signal generator impedance is matched to the biasing circuit by a triple stub, in order to ensure that available signal power from the generator is transferred to the SOA chip in the most efficient manner. Impedance matching is extremely helpful in our case because of the complex impedance presented by the SOA, affected not only by the SOA chip itself, but also by the packaging and the biasing circuit. Moreover, we can employ low loss narrowband impedance matching, thus further improving signal transfer to the SOA, because of the narrowband nature of the OFDM signals (less than 20 MHz around either a 2.5 GHz or 5 GHz carrier).

![Experimental Setup Diagram](Image)

Fig. 2. Experimental Setup (LD: laser diode, VOA: variable optical attenuator, PC: polarization controller, IM: impedance matching, ISO: isolator, BPF: band-pass filter, PD: photodiode, TIA: trans-impedance amplifier).

![Gain Saturation Curve](Image)

![Gain vs. Current Curve](Image)

Fig. 3. a) Gain saturation curve of the SOA biased at 460 mA b) Gain vs. current curve of the SOA for the interesting values of currents for the application; in the inset the same curve is plotted in dB and for a larger current range. Two values of $P_{\text{opt}}$ are considered: -30dBm (solid) and -10 dBm (dashed).

The input optical power $P_{\text{opt}}$ is held constant while the SOA current is modulated by the data signal. The SOA gain is modulated via the current signal, transferring the modulation to the output optical power $P_{\text{opt}}^{\text{OUT}}$ [4-5]. The modulated output passes through an isolator to prevent harmful reflections, a 0.24 nm band-pass filter to select the laser at 1562nm, and a second variable optical attenuator for controlling the power on the photodiode $P_{\text{opt}}$ before the signal analyzer (Agilent E4440A).

As a reference, some of the most important characteristics of our SOA are shown in Fig. 3. The gain saturation can be seen in Fig. 3-a, and the variation of the gain with the SOA injection current in Fig. 3-b. The inset shows the gain in dB, while the main plot is a zoom of the inset in linear scale, in the zone where the SOA has significant gain.

IV. LINEARITY AND NOISE PERFORMANCES OF THE SOA MODULATOR

Since we are dealing with analog complex signals, the linearity of the modulator is the first issue to be investigated. Ours being a narrowband (sub-octave) application, we are only interested in odd-order distortion products, as the even ones can be easily filtered electronically at the receiver. Furthermore, SOA add noise. Thus, in order to identify an optimum operating point we will focus on three parameters: the power of the fundamental component, the 3rd order inter-modulation (ID3) products and the carrier to noise ratio. Recall that when the SOA is saturated the noise level decreases because the amplified spontaneous emission (ASE) level decreases [6].

Fig. 4-a shows the result of the inter-modulation distortion measurements. For these measurements the vector signal generator produced two tones with 1 MHz spacing around 2.5 GHz, and we measured the ratio between the powers of the received tones versus the ID3 products expressed in dBC, i.e. power relative to the carrier (fundamental). The vector signal generator was calibrated to assure accurate measurements; ID3 could be measured to levels as low as -80dBc. We varied the bias point and the level of saturation of the SOA (by varying $I_{\text{DC}}$ and optical power $P_{\text{opt}}$ ) for a fixed modulation power of +8dBm per tone (+11 dBm total). The power of the fundamental component increases with the saturation level because of the greater power on the photodiode; at the same time the ID3 increases because we are in the saturation regime. The shape of the curves is affected by the slope of the curve in Fig. 3-b (linear gain versus the bias current): the fundamental increases with the bias level, and the non-linearity is higher when the linear gain slope is rapidly changing with bias current.
Note that CNR is given in dB/Hz, since the noise is integrated over a 1 Hz bandwidth. In Fig. 4-b the vector signal generator produced one tone at 2.5 GHz, and we measured the carrier-to-noise ratio (CNR) on the signal analyzer varying the SOA bias point, and for various optical input powers. We see in Fig. 4-b the CNR increases monotonically to some maximum value at moderate pump currents. For high pump bias current the CNR stays fairly constant, although small degradation is visible at low saturation. As the SOA pump current increases the desired signal (the fundamental) increases to a maximum. Once reaching moderate pump current (300 mA), the principal noise source is ASE and its beating with the input signal. This noise decreases with deeper saturation, hence the improvement in CNR with increasing pump current and saturation.

Since we have low non-linearity (even for RF powers as high as +8dBm per tone, the ID3 is always below -42 dBc), and an almost flat CNR, for the next sections we choose the working point $i_{DC} = 460\text{ mA}$, in order to maximize SOA gain.

V. PERFORMANCE OF SOA MODULATOR WITH OFDM SIGNALS

Our figure of merit is the bit error rate (BER) versus the RF power modulating the SOA pump current around its bias point of $i_{DC} = 460\text{ mA}$. The optical power incident to the photodetector $P_{PD} = -10\text{ dBm}$ is held constant by adjusting VOA2, so that variations in available gain from the SOA do not interfere with interpretation of our results. We consider three values for the input optical power $P_{IN}^{opt}$ (adjusting VOA1), corresponding to the optical power available from the remote, distributed CW laser source. Fig. 5 shows the bit-error rate results of our analog OFDM signal O/E conversion: dotted lines correspond to the BER without forward error correction (FEC); solid lines correspond to the BER after correction, using the IEEE 802.11 standard FEC with a hard-decision Viterbi decoder. In Fig. 5 the vector signal generator provided an OFDM signal on a 2.5 GHz carrier. As $P_{IN}^{opt}$ increases the SOA becomes saturated, and we can see that the impact of amplifier saturation on the E/O conversion is positive, with decreased BER for greater optical powers.

In Fig. 6 we plot the error vector magnitude (EVM) results for various modulation powers $P_{RF}$ against the optical input power. The dash-dotted line corresponds to a BER lower than $10^{-6}$ on the coded bits (EVM = -22.5 dB, or 7.5%, inferred from the BER measurements of Fig. 5). The figure can be compared to Fig. 3-a, to see that the greater SOA saturation level leads to better performances in terms of EVM (better modulator), and to a loss in optical gain (worse amplifier).
Interestingly, we observe that performance improves when the SOA is operated in saturation. The 3rd order distortion is low enough that operating in the nonlinear saturation regime does not degrade the OFDM signal quality.

The enhancement in performance can be justified by Fig. 7, where we plot the CNR and the noise floor as a function of the optical input power to the SOA $P_{opt}^N$, for various RF powers. The CNR improves because of the lowering of the noise, as we can argue from the dotted line (for a fixed PRF, the power of the carrier does not change with $P_{opt}^N$). Since the power on the photodiode is constant ($P_{opt}^{PD} = -10$ dBm), the contribution of shot noise, thermal noise and of laser relative intensity noise (RIN) is constant. The noise that decreases with the saturation level is then the signal-ASE beating that falls at 2.5 GHz, which is always the dominating noise component, except in deep saturation.

In order to establish the functionality of the SOA as an external modulator for 802.11a (at a carrier frequency of 5 GHz), Fig. 8 shows the comparison of the performance of the conversion with carrier frequency of 2.5 GHz and 5 GHz, where we fixed the saturation level at the amplifier corresponding to the best case in Fig. 5, $P_{opt}^{PD} = -6$ dBm.

In Fig. 8 the SOA is saturated (its input power is -6 dBm) and the received optical power is -10 dBm. The total attenuation introduced is then 17 dB (the gain of the SOA being 13 dB). The penalty to be paid in passing from a 2.5 GHz carrier to a 5 GHz carrier in terms of $P_{RF}$ to achieve BER $= 10^{-5}$ on the bits after FEC is 14 dB. Note that the same BER could be achieved with less RF power and a deeper saturation level, or less RF power and less attenuation. In fact the combination of the free parameters in this application affects the performance, and the tradeoff is between the three of them: optical power at the input of the SOA $P_{opt}^N$, the RF power $P_{RF}$, and the received power $P_{opt}^{PD}$.

**VI. CONCLUSIONS**

We demonstrated that electro-optical conversion of analog signals such as 64-QAM, 54 Mb/s OFDM signals on 2.5 and 5 GHz carriers is possible by direct injection current modulation of an SOA. The SOA can thus be used for amplification in the downlink, and as an external modulator for a distributed optical source in the uplink.

**REFERENCES**


