Signal Amplitude and Phase Equalization Technique for Free Space Optical Communications

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ABSTRACT

We propose a technique for equalizing the amplitude and phase fluctuations of the distorted signal in free space optical (FSO) communications. The technique exploits the dynamic characteristics of a semiconductor optical amplifier (SOA) together with the interferometric properties of a cascaded optical delay interferometer (ODI). By conducting numerical simulation we have investigated the impact of the SOA and ODI critical operating parameters on the performance of the FSO communication system. The obtained results confirm the feasibility of the scheme and its capability of efficiently mitigating the amplitude and phase variations, as quantified by the achievement of acceptable metrics. Thus the technique can enhance the robustness of FSO links against atmospheric impairments, including scintillation, and allow for better quality and more reliable interconnections.

Keywords: free space optical (FSO) communications, signal equalization, semiconductor optical amplifier (SOA), optical delay interferometer (ODI)

1. INTRODUCTION

Owing to the inherent advantages of high bandwidth, absence of interception and interference to other Radio Frequency (RF) systems, small transmitted beam-width, unlicensed spectrum assignment, enhanced level of security and easy, adaptable and cost-effective development, Free Space Optical (FSO) communications have evolved to become a competitive alternative over microwave RF communications [1]. However the potential of this technology is compromised by the existence in the propagation medium of various atmospheric impairments whose randomly and rapidly varying nature degrades the quality of the communicating signal. In particular the impact of scintillation is mostly harmful as it causes intense fluctuations in the amplitude and phase of the received signal, which result in increased error probabilities and strict performance limitations. A variety of techniques have been employed to mitigate this effect, such as spatial diversity [2], aperture averaging [3], temporal-domain detection [4] and error control coding [5].

In this paper we propose a technique for achieving signal amplitude and phase equalization in FSO links, which exploits the dynamic characteristics of a semiconductor optical amplifier (SOA) in combination with the interferometric properties of a concatenated optical delay interferometer (ODI) [6]. For this purpose we have conducted a numerical simulation and analysis to investigate and specify how the SOA and ODI must be designed in terms of their critical parameters so that the pursued goal can be efficiently met. The proposed scheme can help combat the deleterious consequences of scintillation in FSOs links and enable reliable interconnection between parties and platforms which may not necessarily be static but be moving as well, like in Unmanned Aerial Vehicles (UAV) and mobile networks.

2. PRINCIPLE OF OPERATION AND MODELING

Fig. 1 shows schematically the block diagram of the proposed scheme, which comprises of a SOA followed by an ODI. The optical signal that has been communicated in free space enters the setup suffering scintillation-dependent amplitude and phase fluctuations. The initial peak intensity difference and initial chirp parameter of the pulses produced from the signal components that arrive from different directions are due to the signal amplitude and phase distortions, respectively.

In the effort to remove these impairments and restore the signal's quality to an acceptable degree the SOA and ODI must act in a combinational manner upon. More specifically, the amplitude fluctuations can be compensated if they are converted somehow to amplitude variation of the opposite magnitude. This can be achieved by exploiting the phase shift imparted on the received signal due to self-phase modulation (SPM) in the SOA [7]. Given that the pulses inserted in the SOA originate from strongly attenuated multipath signal components, their power content is not capable of saturating the SOA gain to an extent that SPM can sufficiently manifest. Thus in order for SPM to become significant we must suitably choose the SOA alpha factor, α, and small signal gain, G_{SS}, on which this effect depends [7]. With this condition the SPM-induced phase shift is larger for the stronger signal components than for the weaker ones. Therefore if we properly adjust the ODI delay, $\Delta\tau$, and phase offset, $\Delta\varphi$, we can benefit from this phase discrepancy by making at the ODI output the former components interfere destructively and be clamped and the latter interfere constructively and be enhanced, so that their amplitude wandering is balanced. The signal phase fluctuations, on the other hand, correspond to a different amount of equivalent initial chirp parameter assuming Gaussian-shaped pulses [7]. In the extreme case this chirp parameter is positive and is added to the red chirp incurred by SPM in the SOA [7]. This means that the signal components experiencing larger instantaneous frequency deviation are more spectrally broadened to the longer sideband than those whose phase response variation per time increment is smaller. Thus if a larger portion of the broadened spectrum is blocked for the higher chirped signal components and passed for the lower chirped ones then the uneven red shift and subsequently the phase fluctuations can become more equalized. This can be done by exploiting the filtering discrimination capability that the ODI exhibits thanks to the form of its transfer function [6]. For this purpose its wavelength at transparency must be negatively detuned through the proper selection of its delay so that its transmittance is decreased as the wavelength is increased. In this manner the broadened signal constituents can be attenuated in direct analogy to the degree they have been red shifted, which eventually smoothens the signal phase variations. To this end and provided that it is properly designed the SOA-ODI combination can regenerate in amplitude and phase and concurrently amplify the received signal so that its quality can be restored to a level that guarantees the good performance of the FSO communication system.

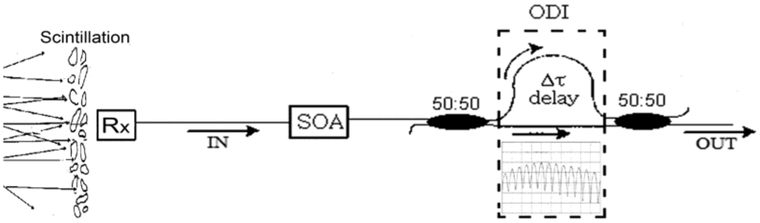

Figure 1. Proposed SOA-ODI FSO signal amplitude and phase equalization scheme.

In order to simulate the operation of the proposed scheme, we need to provide expressions for the power, *P(t),* and chirp $\Delta v(t)$, at the output of the SOA and ODI. Starting with the power, we have [6]

$$P_{SOA}(t) = P_{in}(t)\exp\left[h(t)\right],\ P_{ODI}(t) = \frac{1}{4}\left\{P_{SOA}(t) + P_{SOA}(t-\Delta\tau)+2\sqrt{P_{SOA}(t)P_{SOA}(t-\Delta\tau)}\times\cos\left[\Delta F(t)+\Delta\varphi\right]\right\} \qquad (1)$$

for signal components whose corresponding pulses launched into the SOA have a return-to-zero coding Gaussian-shaped power profile, $P_{in}(t) = P_{peak}\exp\left[-(1+jC)\left(4\ln 2t^2D^2/T^2\right)\right]$, where P_{peak} and C are their distinguishable peak power and initial chirp parameter, respectively, and $D = 4$ is their duty factor at a repetition interval T = 100 ps. Moreover $\Delta F(t) = F_{SOA}(t) - F_{SOA}(t-\Delta\tau)$ is the phase difference between the direct and delayed replica of the signal inserted in the ODI, where $F_{SOA}(t) = 2\ln 2Ct^2D^2/T^2 - \alpha h(t)/2$ is the phase of the amplified signal and *h(t)* is the SOA integrated gain that obeys the following first-order differential equation [7]

$$\frac{dh(t)}{dt} = \frac{\ln(G_{ss})-h(t)}{T_{carrier}} - \frac{P_{in}(t)}{E_{sat}}\left\{\exp\left[h(t)\right]-1\right\} \qquad (2)$$

where G_{ss}, $T_{carrier} = 75$ ps and $E_{sat} = 1.5$ pJ are the SOA small signal gain, carrier lifetime and saturation energy, respectively. The chirp, on the other hand, is given by [7] $\Delta\nu_{SOA,ODI}(t) = -(1/2\pi)\left(dF_{SOA,ODI}(t)/dt\right)$, where $F_{SOA}(t)$ was defined above, and [6] $F_{ODI}(t) = F_{SOA}(t-\Delta\tau) - \arctan(A/B)$, where $A = 1+\sqrt{P_R(t)}\cos\left[\Delta F(t)\right]$, $B = \sqrt{P_R(t)}\sin\left[\Delta F(t)\right]$, $P_R(t) = P_{SOA}(t)/P_{SOA}(t-\Delta\tau)$. Therefore the required power and chirp functions can be calculated by numerically solving (2) to find *h(t).* This is done according to the procedure described in [6] for an exemplary 127-bit long pseudorandom pulse pattern. In this sequence the presence of a pulse of some peak corresponds to an aggregate of received signal components having the same magnitude, while the absence of a pulse implies that the recombined signal components have cumulatively been cancelled out.

3. RESULTS

The performance of the scheme is evaluated against the signal peak amplitude fluctuation (*AF*) and chirp fluctuation (*CF*) at the output of the ODI, which are defined as $AF\ (\text{dB}) = 10\log\left(P_{\max}/P_{\min}\right)$ and

$CF = \left(\Delta\nu_{\max}/\Delta\nu_{\min}\right)$, where $P^{1}_{\max}$ and $P^{1}_{\min}$ is the maximum and minimum peak power, and $\Delta\nu_{\max}$ and $\Delta\nu_{\min}$ is the maximum and minimum peak red chirp that depends on the initial chirp parameter, of the signal pulses, respectively [6]. From a simulation perspective the different *AF* values are implemented by using in Matlab software the random function and adding or subtracting its product to the peak of each pulse. Thus in the following we present simulation results for the influence of the ODI delay and phase offset and the SOA linewidth enhancement factor and small signal gain on the two defined metrics. Our ultimate aim is figuring-out how these critical operating parameters must be selected so that the proposed signal amplitude and phase equalization technique is efficiently applied. This is done for three representative initial *AF* and chirp parameter values of the pulses at the input of the SOA-ODI configuration, namely for cases/scenarios 1) (*AF*, *C*) = (1 dB, 1), 2) (1.5 dB, 2) and 3) (2 dB, 3). These combinations denote low, medium and high performance degradation, respectively, and allow us to fully characterize the efficiency of the proposed signal equalization technique.

Fig. 2(a)-left column shows that the *AF* is reduced in the entire ODI delay span from 0 ps to 20 ps across which the specific parameter is varied. The decline is higher for the third combination of *AF* and *CF*, for which the initial peak intensity difference and initial chirp parameter are larger, but still the *AF* is over 1 dB. In the first and second case the *CF* remains degraded for the lower examined values of $\Delta\tau$ (Fig. 2(a)-right column) and is further aggravated for the third case. Nevertheless, there is a range of $\Delta\tau$ values where we can obtain small *CF*, but this does not cover the third situation too. We also underline that if the ODI delay is arbitrarily increased then the chirp and pulse profiles become strongly distorted [6]. This fact must definitely be taken into account in the design procedure. In Fig. 2(b)-left column the *AF* is drastically increased above its initial values for all three cases as the ODI phase offset reaches $-\pi$. The *CF* is reduced for specific values of $\Delta\varphi$ only in the first two scenarios (Fig. 2(b)-right column).

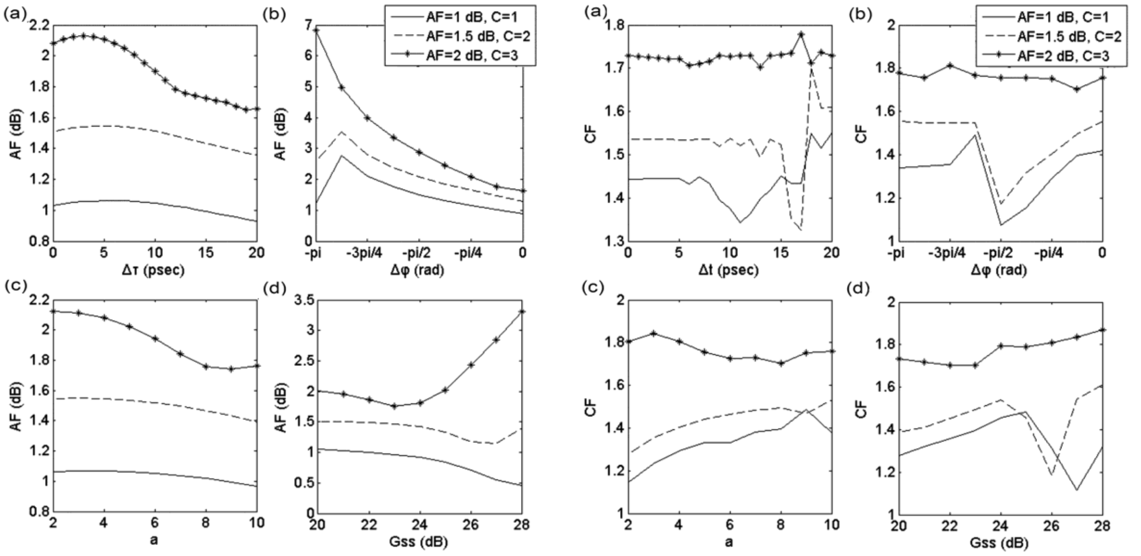

Figure 2. Peak amplitude fluctuation-AF (left) and chirp fluctuation-CF (right) at ODI output vs. (a) ODI delay, (b) ODI phase offset, (c) SOA linewidth enhancement factor and (d) SOA small signal gain.

The influence of the SOA linewidth enhancement factor, α, on the *AF* is depicted in Fig. 2(c)-left column, where we note that the *AF* is reduced with α for all performance scenarios. In contrast the *CF* is increased with α for the low and medium performance degradation cases while this parameter has no significant effect under severe conditions, like the third one (Fig. 2(c)-right column). The evolution of the *AF* versus the SOA small signal gain, G_{ss}, is portrayed in Fig. 2(d)-left column. From this figure we observe that as this parameter is altered from 20 dB to 28 dB the *AF* is increased in the second and third situation and this deterioration is more pronounced for the latter. Moreover the *AF* can be improved against G_{ss} only in the first situation. Additionally, the *CF* is increased up to about the middle of the G_{ss} range of values, but then experiences a significant fall, which occurs after 25 dB in the first case and 24 dB in the second (Fig. 2(d)-right column). For the third case the *CF* remains constantly poor despite the change of G_{ss}.

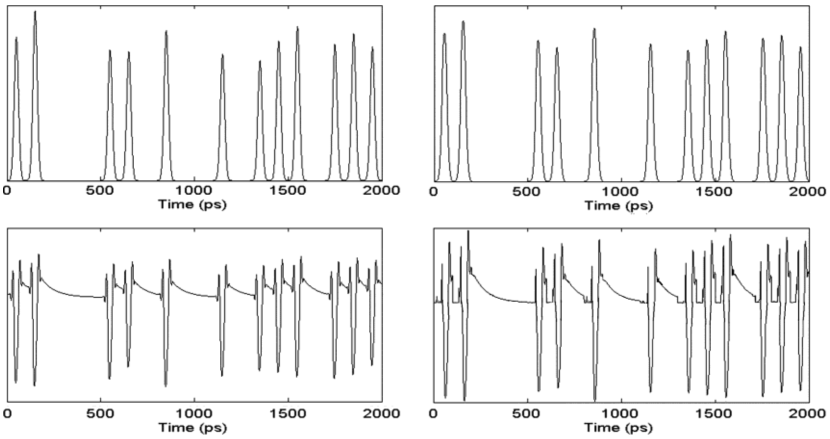

Figure 3. Signal pulse (top) and chirp profile (bottom) without (left) and with (right) equalization technique.

From the examination and analysis of the foregoing curves it can be deduced that for all the critical parameters *CF* cannot be improved when we have both high initial peak intensity difference and initial chirp. Consequently, the proposed technique is not efficient to be used when the signal phase fluctuations result in high performance degradation. Furthermore, the simulation results suggest that in order to select the critical operating parameters in an optimum way we should make a compromise between *AF* and *CF*. Thus by choosing $\Delta\tau = 13$ ps, $\Delta\varphi = -\pi/8$, $\alpha = 9$ and $G_{ss} = 26$ dB we can efficiently achieve such trade-off. Fig. 3 shows the signal pulse and chirp profiles for a representative 20 bit-long data frame, with and without applying the equalization technique, for the case of medium performance degradation. This combination results indeed in acceptable *AF* = 0.94dB, as opposed to *AF* = 1.5 dB without the ODI. Similarly the *CF* is dropped from 1.65 dB after the SOA to 1.15 dB after the ODI. These quantitative improvements are directly reflected on the pulse and chirp amplitude variations, which become more smoothened.

4. CONCLUSIONS

The capability of an ODI-assisted SOA configuration to compensate for the amplitude and phase fluctuations in FSO communications has been investigated and demonstrated by means of numerical modelling. The interpretation of the simulation results has revealed that the scheme can handle, and be efficient up to, a certain degree of performance degradation. For this purpose the SOA and ODI parameters must be appropriately chosen and combined so that the incurred amplitude and chirp fluctuations can be mitigated and dropped to a tolerable level. The proposed technique can be useful for combating the deleterious consequences of atmospheric impairments, including scintillation, and for enhancing the performance of FSO communications.

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