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Vertical cavity surface emitting laser based hybrid fiber-free space optic link for passive optical network applications

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ABSTRACT

In this work, a hybrid architecture employing Vertical Cavity Surface Emitting Laser (VCSEL) based Single Mode Fiber (SMF) link followed by Free Space Optic (FSO) transmission, is investigated. The VCSEL is biased below threshold to generate short optical pulses, which is coded in NRZ format. After the 20 km SMF link, a splitter divides the received power into two branches. One portion is coupled to a PIN photodiode for receiver operation, whereas the remaining power is coupled to a lens for free space transmission. The VCSEL-SMF-FSO link is simulated and performance measures are computed and verified with link budget calculation. The maximum FSO link distances under different weather conditions and coupling ratio were found. For BER $\leq 10^{-12}$, under clear weather, the maximum attainable FSO link lengths for 1.25, 2.5, 5 and 10 Gbps data rates are found to be 0.205 km, 0.16 km, 0.14 km and 0.11 km respectively. The same procedure when extended to snowy conditions, yield FSO link length of 155 m, 125 m, 110 m and 90 m for 1.25, 2.5, 5 and 10 Gbps data rates under similar BER performance. The impact of fractional power coupled to FSO link was analyzed for 5 Gbps by varying the splitting ratio from 80:20 to 86:14. The optimum ratio up to which both SMF and the cascaded link system meet the required BER for Gigabit PON application is also determined.

1. Introduction

Vertical Cavity Surface Emitting Lasers (VCSELs) are low cost optical sources that find applications in various fields of research. Long wavelength VCSEL and Standard Single Mode Fiber (SSMF) together serves effectively for Passive Optical Network (PON) applications. B. Shin et al. [1] investigated transmission of 10 Gbps optical NRZ signals through 1550 nm VCSEL and 20 km SMF with 10^{-9} BER and 2.4 dB dispersion penalty. They used gain saturation of Reflective Semiconductor Optical Amplifier (RSOA), to cooperate optical pulse distortion due to VCSEL's frequency chirping and SMF's chromatic dispersion. Boiyo et al. [2] demonstrated pure optical laser-to-laser wavelength conversion with two 1550 nm VCSELs and transmitted 8.5 Gbps NRZ data over 24.7 km SMF. Kim et al. [3] implemented transmission of LTE-A signals with 24 carriers of 20 MHz each over SSMF for 20 km, using TO-CAN packaged 1550 nm VCSEL. Zhou et al. [4] reported direct modulation of 1500 nm VCSEL and transmitted 10.7 Gbps OOK and 4-PAM signals over SSMF. With optimized extinction ratio and post detection electrical equalization, OOK signals provided a maximum reach of 80 km.

Recently, VCSELs are also investigated for Free Space Optic (FSO) Communication. Latest researches in the field of FSO deal with link performance under various weather conditions, atmospheric turbulence and dispersion effects. Katsilieris et al. [5] used log normal (weak), gamma-gamma (moderate to strong) distributions for modelling turbulence effects and performance measures like

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outage probability and average channel capacity are calculated. The average channel capacity for 5 km FSO link at 17 dB SNR using log normal was found as 18.63 b/s/Hz and 5.46 b/s/Hz for gamma-gamma channel.

Bouhadda et al. [6] investigated the impact of dispersion effect due to atmospheric pressure and temperature on NRZ-OOK FSO transmission system. For a propagation distance of 7.5 km, a broadening factor of 2.39 for input pulse width of 300 fs was estimated. M. Singh [7] reported the performance of 2.5 Gbps NRZ FSO link operating at 1550 nm under rain conditions. For BER $\leq 10^{-9}$, the maximum FSO link length is found as 1250 m. When Erbium-Doped Fiber Amplifier (EDFA) was used as pre-amplifier, the distance increases to 1675 m. Esmail et al. [8] developed a probabilistic model for signal attenuation in fog, (dense, thick, moderate and light) based on the measurements collected from different countries. Under thick fog, for link length of 0.5 km and 0.2 km, channel capacities are 5 bits/s/Hz and 22 bits/s/Hz respectively. Zhang et al. [9] have done numerical simulations and found BPSK to be robust, turbulence resistant and suitable for FSO systems. Kaur et al. [10] evaluated error performance and outage probability of FSO link along with MIMO and aperture averaging techniques under various weather conditions. Stassinakis et al. [11] observed that GVD effect is significant for short Gaussian pulses under long propagation distances. To stabilize the free space output beam of optical phased array, Mekhiel and Fernando [12] have proposed a novel heterodyne feedback scheme.

From the literature, it is observed that free space optics has been studied extensively for modern optical communication. However, a very limited number of contributions exist for hybrid fiber and FSO system. Bohata et al. [13] demonstrated a combined link of aged optical infrastructure and FSO. They transmitted polarization multiplexed LTE signal in one study and 10 Gbps OOK NRZ signal in another. Nguyen et al. [14] demonstrated a gigabit bandwidth capable solution for 5G backhaul networks using PON, FSO and RF technologies in parallel. For FSO, an optical regeneration mechanism is used. Yu et al. [15] proposed and investigated a bidirectional long-haul optical fiber transmission across bridge with hybrid Fiber-FSO system.

In all the above cases, EDFAs were used as optical amplifiers and detailed characteristics of laser operation were not provided. However, wavelength and optical power were considered. Whereas in the present work, a novel approach of transmitting data over a low cost VCSEL, 20 km SSMF and FSO cascaded from the same source is discussed. This simulation work utilizes a VCSEL and a passive optical network without an optical amplifier (EDFA). The received optical power at the venture of 20 km fiber link is divided and 80% of the power is propagated into free space. Remaining power is utilized for optical receiver in the wired (fiber) link. The optical power for free space transmission is obtained from SMF by a lens mechanism, thereby eliminating the need of a repeater. The essential blocks of a typical PON based hybrid FSO link is pictured in the Fig. 1. The FSO channel is analyzed under clear weather, rain and snow conditions. For modelling the FSO, not only attenuation, but geometric loss and coupling loss of lens are also considered. The generated optical pulses from VCSEL has pulse width in the order of hundreds of picoseconds which cause negligible pulse broadening in FSO channel compared to Standard Single Mode Fiber (SSMF). The entire link model is simulated in Matlab platform.

2. VCSEL diode characteristics

An 1.55 μm single transverse mode business VCSEL (RayCan Co.) has been taken for the study. The device is a TO-56 ponytail VCSEL based on InAlGaAs active region and InAlGaAs/InAlAs mirrors [16]. A Spin Flip Model (SFM) based standard VCSEL rate equations Eqs. (1)–(5) considered in this work are,

$$\partial N/\partial t = \gamma\mu(N_{th} - N_t) - \gamma(N - N_t) - G_N(N - N_t)S \tag{1}$$

$$\partial S/\partial t = \frac{\beta_{SF} N \gamma^2}{2\kappa} + 2\kappa S\left(\frac{(N - N_t)}{(N_{th} - N_t)} - 1\right) \tag{2}$$

$$P = \frac{eS}{\tau_p F} \tag{3}$$

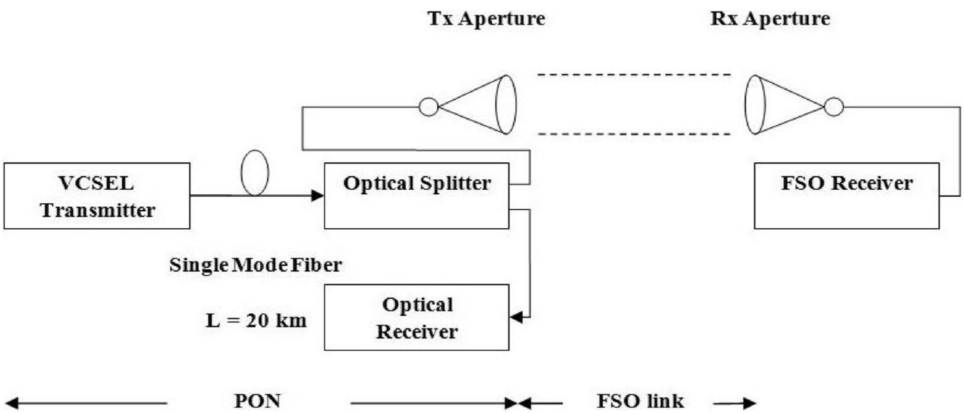

Fig. 1. A simple PON based hybrid SMF-FSO link.