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Mode division multiplexing and dense WDM-PON for Fiber-to-the-Home

Yousef Fazea

InterNetWorks Research Laboratory, School of Computing, Universiti Utara Malaysia, Sintok-Kedah, 06010, Malaysia

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ABSTRACT

In this paper, a dense wavelength division multiplexing - passive optical network (DWDM-PON) architecture was designed using vertical cavity surface emitting laser (VCSEL) arrays for mode division multiplexing (MDM) of Laguerre-Gaussian (LG) modes LG_{12}, LG_{15}. LG_{18}, LG_{111} and LG_{114}. A data rate of 25Gbit/s has been achieved at a central wavelength 1550.12 nm with a spacing of 1.6 nm. Transmission performance was compared for multimode fiber (MMF) lengths of 200 m to 1 km. The modal performance has been evaluated using spatial electric field, electric signal, eye diagram and bit-error-rates (BER).

1. Introduction

Triple play services comprising video, audio and data have become part and parcel of today's network [1]. The increase of connected users over the last decade requires more bandwidth in Fiber-to-the-Home (FTTH) networks [2]. In view of the rapidly increasing bandwidth demand from FTTH users, networks supporting up to l0Gbit/s is insufficient for accommodating the current increasing demands. Network providers have been left with no clear choice as to which FTTH architecture should be considered to accommodate their requirements. Despite the high deployment cost of the distinct FTTH based on Passive Optical network (PON) technology and point-to-multipoint architecture [3], Wavelength Division Multiplexing (WDM)-PON has garnered significant attention due to its high bandwidth, high-speed access, large capacity, channel independence, ease of management, format transparency, network security and upgradability [4,5]. According to [6], certain requirements for future carriers that must be met include: (a) compatible with the legacy network, (b) flexible, upgradable and manageable bandwidth (d) provide huge bandwidth capacity (d) better performance with acceptable cost. The new access technology WDM-PON can potentially satisfy the above criteria and has emerged as the best prospect for last mile connectivity compared to other wired architecture [7]. To increase the bandwidth of WDM systems, Mode Division Multiplexing (MDM) [8–11] has tremendous potential for enhancing the bandwidth of the optical fibers by using higher-order modes as independent data channels and engineering the channel transfer function. This adds another multiplexing dimension to the conventional wavelength dimension [12–15]. MDM is viable through a number of approaches such as generating matching eigenfunction wavefronts [16–19], adaptive optical equalization [9,20–25], modal decomposition techniques [26,27], offset launches [28–30] as well as spatial filters based on single mode fibers {SMF) [31], phase masks [32] and gratings [33,34].

In this paper, we designed and analyzed a new DWDM-PON architecture incorporating mode division multiplexing of Laguerre-Gaussian modes using vertical- cavity surface-emitting laser arrays (VCSELs). Section 2 describes the new DWDM-PON architecture with MDM. The results are then analyzed in Section 3.

E-mail address: yosiffz@internetworks.my.

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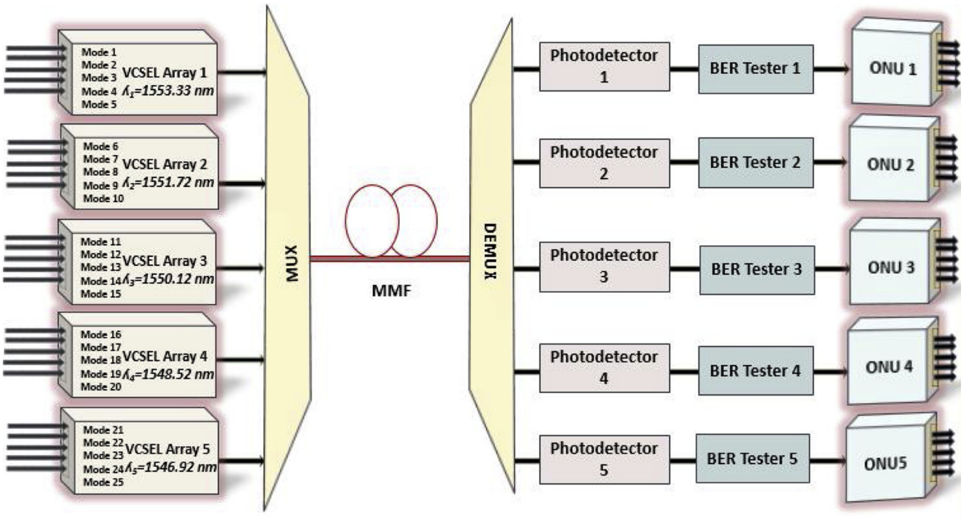

Fig. 1. MDM-WDM multiplexing model.

2. DWDM-PON architecture with MDM

A DWDM-PON modal multiplexing architecture with five VCSEL arrays lasing at five wavelengths, λ_1 to λ_5 as between 1546.92 nm and 1553.33 nm was simulated using Synopsis OptSim 5.2 [35], and MATLAB [36] as shown in Fig. 1. The wavelength separation was based on the ITU grid, to 1.6 nm and centered at 1550.12 nm. The five VCSEL arrays are driven by separate A pseudorandom binary sequence (PRBS) electrical signals to generate sequences, which are offset from one another. A non-return-to-zero (NRZ) modulation scheme is used. The VCSEL arrays emit power in the Ex-polarization only. The power from each VCSEL array is assumed to be emitted uniformly into 5 μm Laguerre-Gaussian (LG) beams.

Five LG modes are excited in each VCSEL array. Thus the five VCSELs comprising five LG modes create a total 25 channels. The LG modes may be described by a radial order m and azimuthal order l as:

$$\psi(r,\phi) = \alpha.\left(\frac{2r^2}{w_0^2}\right)^{L/2}.\ L_m^l\left(\frac{2r^2}{w_0^2}\right).$$
$$\exp\left(-\frac{r^2}{w_0^2}\right).\ \exp\left(j\frac{\pi r^2}{\lambda R_o}\right).\begin{cases}\cos(L\phi) & ,\ l\geq 0\\ \sin(L\phi) & ,\ l<0\end{cases} \tag{1}$$

For each VCSEL array, the azimuthal mode numbers is constant at $l = 1$ whilst different radial mode numbers, $m = 2, 5, 8, 11, 14$ were excited. The transverse modal electric fields are calculated analytically based on the wavelength of each VCSEL. The power-coupling coefficient between the output field of each VCSELs and each transverse modal field of the MMF is calculated as follows:

$$c_{lm} = \int_0^{2\pi}\int_0^{\infty} E_{lm}^i(r,\phi)\cdot e_{lm}^*(r,\phi)\cdot r\ \ dr\ d\phi \tag{2}$$

where E_{lm} is the incident electric field on the multimode fiber (MMF) and e_{lm} is the transverse modal electric field for LG1m. The total incident spatial electric field at the MMF input from each VCSEL may be described as:

$$E_{lm}^i(r,\phi,t) = E_{lm}^i(t)E_{lm}^i(r,\phi) = \left[\sum_l\sum_m c_{lm}e_{lm}(t)\right]E_{lm}^i(r,\phi) \tag{3}$$

The 25 channels are multiplexed into MMF. The MMF refractive index is sampled from a manufactured fiber, as shown in Fig. 2. The refractive index profile parameter is where $\alpha = 1.87$. The refractive index affects the distribution of the optical power and velocities of propagating modes. Our model takes into consideration modal and chromatic dispersion, attenuation, and power modal coupling. At the receiver side, signals from each wavelength were detected by separate photodetector arrays and delivered to separate Optical Networking Units (ONUs). Each photodetector array extracted five LG modes corresponding to the VCSEL array at the transmitter. Each received data signal was analyzed using spatial electric field, electric signal, eye diagram and bit-error-rates (BER).

3. Results and discussion

Spatial fields for 1550.12 nm channel before and after the multiplexer were analyzed. Fig. 3(a) shows the average spatial field for Data Channel 11 to 15 before the multiplexer whereas. Fig. 3(b) shows the average spatial field for Data Channel 11 to 15 after the demultiplexed. Distortion in the wavefront is visible due to power modal coupling from and into other modes. The effects are also

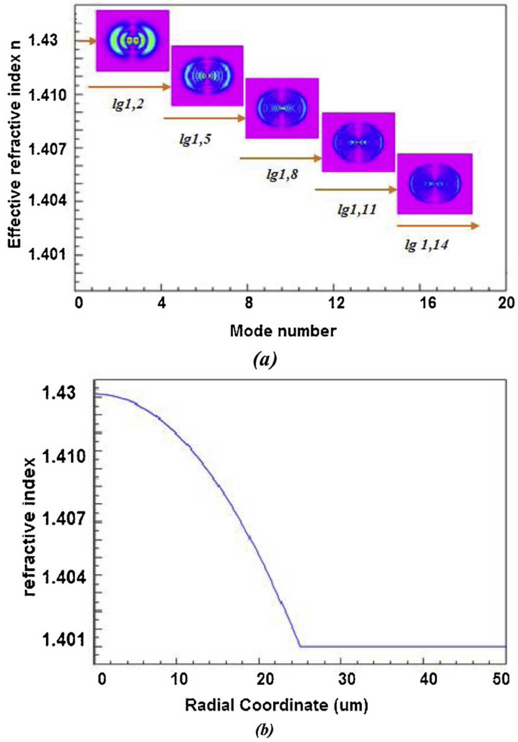

Fig. 2. Corresponding LG mode profile (a) Index profile of manufactured MMF.

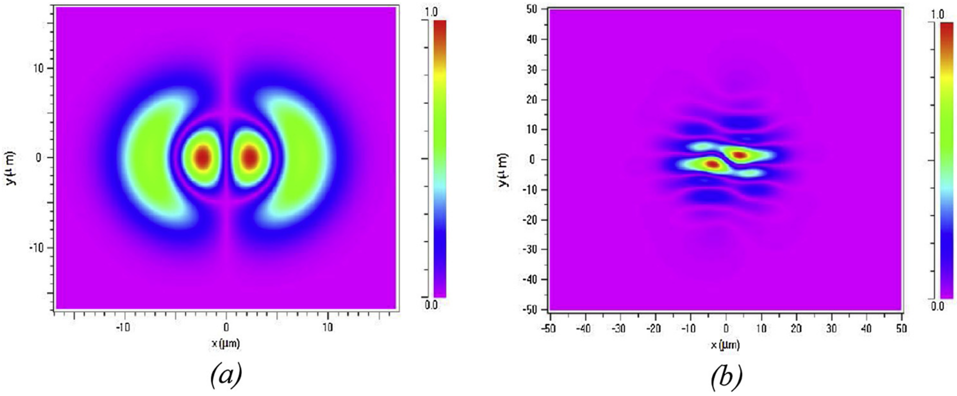

Fig. 3. Spatial electric field before (left) and after (right) MMF for wavelength 1550.12 nm at 1 km.

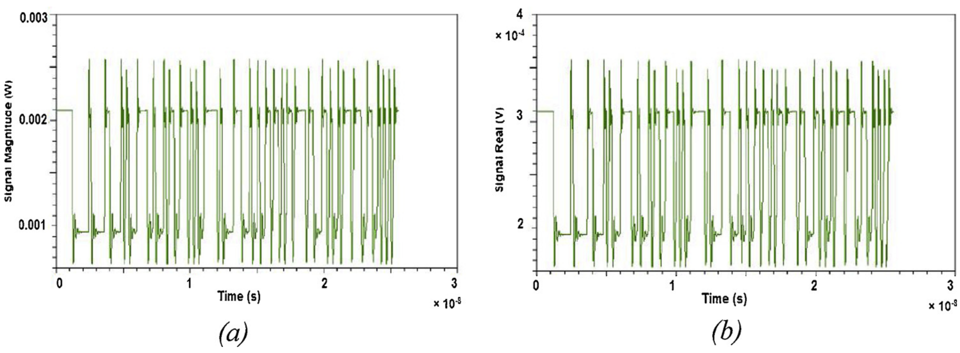

Fig. 4. Spatial electric field before (left) and after (right) MMF for wavelength 1550.12 nm at 1 km.

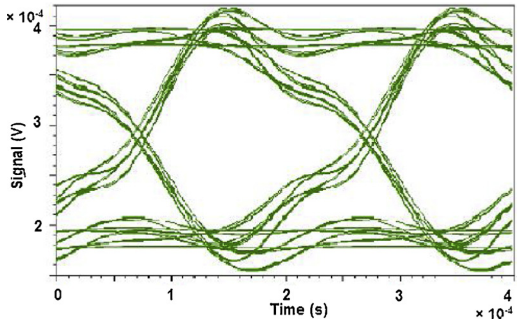

Fig. 5. Eye diagram after multiplexer for 1550.12 nm at 1 km.

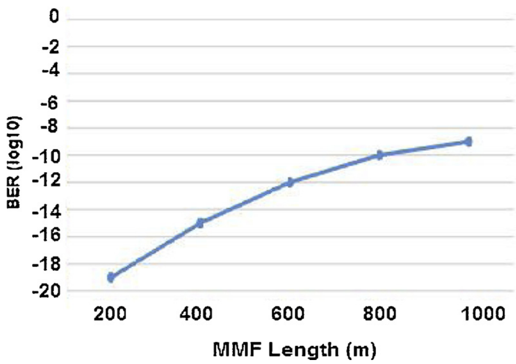

Fig. 6. BER at different MMF length.

visible from the electrical signal in Fig. 4(a) before the multiplexer and Fig. 6(b) after the demutiplexer. The electrical signals after the demultiplexer are no longer uniform due to power coupled from and out into other modes. All eye diagrams are open after the demultiplexer. A sample eye diagram after the demultiplexer for the average channels 11–15 is given in Fig. 5. All channels achieved an acceptable (BERs) of less than 10^{-9} for MMF lengths less than 1 km. The BER generally degrades with distance from 200 m to 1 km as shown in Fig. 6. The maximum achievable MMF length with an acceptable BER of less than 10^{-9} is 1 km. Thus, this architecture is suitable for small private residential areas where each ONU may be used for a particular wavelength to serve a single ONU and the LG modes may be used for delivering various services such as data, audio, television streaming and surveillance monitoring to a single residence.

4. Conclusion

In this paper, a 25-channel hybrid DWDM-PON and MDM architecture utilizing five LG modes per wavelength and five wavelengths has been designed. An aggregate data rate of 25Gb/s was achieved for a distance up to 1 km. Thus, this architecture is suitable within small private residential areas where each wavelength may serve a single ONU and the LG modes may be used for delivering various services such as data, Audio, television streaming and surveillance monitoring to a single residence. Future work will investigate the potential of equalization techniques for extending the maximum achievable MMF length.

Disclosure statement

No potential conflict of interest.

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