A Novel Radio over Fiber System for Long Haul Single-Mode-Fiber Transmission

Anindya Sundar Das, Banibrata Bag, Akinchan Das, Ardhendu Sekhar Patra

***Abstract* — We have proposed and demonstrated a novel architecture of a radio over fiber (RoF) system in this paper. In this downlink system, the base band data signals are carried by the optical millimeter-wave generated at the central station and converted to the electrical RF signal by a converter at the base station before we distribute them through antenna. Here we generate and transmit the optical millimeter-wave by using external modulation technique and carrier suppression method. The performance is investigated by the good eye diagram and the significantly low BER at different lengths of the single mode fiber (SMF).**

***Index Terms* —RoF system, Optical carrier suppression, Long haul transmission, Bit error rate, Q-factor.**

I. INTRODUCTION

The radio over fiber system (RoF) is one of the promising scheme for the future broad band wireless communication system such as mobile communications, hotspots etc. In its downlink system, the base band data signals are carried by the optical mm-wave generated at the central station and converted to the electrical radio frequency (RF) signal by a converter at the base station before we distribute them through antenna. Various schemes for RoF system have been proposed. But these are suitable for the short range application by using multimode fiber as in [1]. The single mode fiber (SMF) is avoided because of the large power loss. But compared with the conventional high frequency wireless system, ROF system shows many advantages such as low cost, high performance huge bandwidth and long distance transmission [2]. The optical millimeter-wave generation is a popular approach for RoF transmission. Several methods are discussed in the previous works by Brown et.al [2] and Yu et. al [3]. These methods are suitable for maximum of 80 km transmission [3]. The external modulation technique is suitable for the optical mm-wave generation [4]. The dispersion effect causes the degradation of the transmission performances. To reduce the effect, several approaches are developed in [5], [6].

In this paper we have configured a design which is capable for gigabit Ethernet transmission. The external modulation technique is used here for optical carrier suppression. In order to reduce power fading at the receiver end the carrier suppression is needed. As the sidebands are carrying information, the suppression of the carrier will increase the dynamic range of the fiber optic link and also the receiver sensitivity. The SMF is used for transmission optical signal to the receiver. The bit error rate (BER) and eye diagrams have been investigated for different SMF lengths of our long-haul transmission.

II. PRINCIPLE

The continuous light wave (CW) is represented by $E_0(t) = a_c \cos \omega_c t$.The optical carrier is suppressed the OCS optical mm wave mainly consists of two sidebands $(\omega_c - \omega_m)$ and $(\omega_c + \omega_m)$ and it can be expressed as

$$E_1(t) = a(t)[a_{-1} \cos(\omega_c - \omega_m)\, t + a_0 \cos \omega_c t + a_{+1}\cos(\omega_c+\omega_m)t] \quad (1)$$

Here a_0 and $a_{\mp 1}$ is the relative amplitude of the carrier and its first order sidebands, but a_0 is small. There are higher harmonics in real system because of the remodulation and nonlinearity of the modulator, but they are too small to be considered. Considering the Fourier transform $\{A(t)\} = A(\omega)$, the power spectrum density can be expressed as

$$P_1(z,\omega) = F\{E_1(z,t)\}.F\{E_1(z,-t)\} = 1/4[a_0^2\{a(\omega - \omega_c)a(-\omega + \omega_c) + a(\omega + \omega_c)a(-\omega - \omega_c)\} + a_{+1}^2\{a(\omega - \omega_c - \omega_m)\, a(-\omega + \omega_c + \omega_m) + a(\omega + \omega_c + \omega_m)\, a(-\omega - \omega_c - \omega_m)\} + a_{-1}^2\{a(\omega - \omega_c + \omega_m)a(-\omega + \omega_c + \omega_m) + a(-\omega + \omega_c - \omega_m)\}] \quad (2)$$

Here we assume that the spectra of carrier and sidebands do not overlap each other. The optical carrier is very small and the sidebands at $(\omega_c \mp \omega_m)$ are the main components, so the bandwidth in the power spectrum density is about $2\omega_m$.There are some optical filter placed at the output end of the optical modulator. These filters are use to suppress and remove out the carrier. Thus the millimeter-wave can be generated. Theoretically we have the expression for the unfiltered photocurrent at the receiver end which is given below:

$$I_1(t) \approx \left(\tfrac{1}{2}\right)\mu a^2(t)[a_0^2 + (a_{+1}^2 + a_{-1}^2)] + \mu a^2(t)\ \{[a_0 a_{+1} + a_0 a_{-1}\cos\omega_m t + a_{+1}a_{-1}\cos\omega_m t \quad (3)$$

The current includes direct current component and radio frequency components. When the optical carrier and the electrical drive signal are applied to an optical phase modulator the optical carrier suppression is happened. Due to optical carrier suppression, the current mainly consists of DC component and harmonic component at $2\omega_m$. After filtering the photocurrent becomes:

$$I_2(t) \approx \tfrac{1}{2}\mu(a_{+1}^2 + a_{-1}^2) + \mu a_{+1}a_{-1} \cos 2\omega_m(t - \beta'(\omega_c)z) \quad (4)$$

After the transmission over SMF of length 'z', the millimeter wave becomes:

$$E_2(z,t) = a_{-1} \cos[(\omega_c - \omega_m)t - \beta(\omega_c - \omega_m)z] + a_0 \cos[(\omega_c)t - \beta(\omega_c)z] + a_{+1}\cos[(\omega_c+\omega_m)t - \beta(\omega_c+\omega_m)z] \quad (5)$$

Here $\beta(\omega)$ is the propagation constant, which is dependent on the half wave voltage V_π.

Manuscript received on March, 2013.

Ardhendu Sekhar Patra, School of Applied Science, Haldia Institute of Technology, Haldia, West Bengal, India.

Anindya Sundar Das, School of Applied Science, Haldia Institute of Technology, Haldia, West Bengal-, India.

Banibrata Bag, Electronics & communication Engineering, Haldia Institute of Technology, Haldia, West Bengal, India.

Akinchan Das, Electronics & communication Engineering, Haldia Institute of Technology, Haldia, West Bengal, India.

There is no fading in the dc component and RF harmonic at $2\omega_m$, but if the carrier sideband is not suppressed completely, RF harmonic at ω_m shows fading with the period $T = f_m^{-2} D^{-1} \lambda_c^{-2}$ and its amplitude is proportional to the amplitude of the remainder of the optical carrier at ω_c. At $a_0 \rightarrow 0$, the full optical carrier suppression will eliminate the fading harmonic at ω_m. In SMF, each optical frequency travels through the fiber at different velocities due to chromatic dispersion. If 'D' is the dispersion parameter and P_{rf} is the RF power of the generated radio frequency f_m, then

$$P_{rf} \propto \cos[\frac{\pi L D}{c} \lambda_c^2 f_m^2] \qquad (6)$$

Where L is the length of the SMF and λ_c is the carrier wavelength. From (6) it can be said that the fiber length L is limited by: $L < \frac{\eta c}{2B\lambda_c^2 D f_m}$ (7)

Where η is the duty cycle and B is the data-rate. For NRZ signal η = 1. The eye diagram closes gradually as the signals are transmitted along the SMF. When the transmission distance approaches L, the eye closes completely. Thus the eye closure is depends upon the data rate, duty cycle, radio frequency and the fiber dispersion. The detected RF current mainly includes the harmonic at $2\omega_m$, which shows no fading and has larger amplitude than that of harmonic at ω_m. Because of that the odd order sidebands are suppressed by the optical filter. As the optical signal passing through the fiber the optical sidebands will sift and the width will reduce. As the transmission length approaches to L the width disappears and the eye diagram is closed. If we use low bit rate and low RF, then long haul transmission can be possible according to (7). The reduction in the chromatic dispersion in SMF can help in sending data to a long distance through optical millimeter-wave.

III. EXPERIMENTAL SETUP

The experimental set up is shown in the fig. 1. A continuous wave (CW) laser, having wavelength of 1550nm is used as a source. The signal is modulated by Mach-Zehnder modulator, driven by an NRZ electrical signal with 1 Gb/s pseudorandom bit sequence (PRBS) and a word length of 2^{11}-1. The modulated signal is passing through an erbium doped fiber amplifier (EDFA), variable optical attenuator (VOA) and a polarizer controller (PC) which has symmetry factor of 10. Then the optical signal is modulated by a dual arm $LiNbO_3$-Mach-Zehnder (Li-MZM) modulator which is biased at V_π (switching bias voltage) and driven by two complementary 50 GHz RF sinusoidal clocks. It is used to realize the optical carrier suppression. The modulated signal is fed into an EDFA and variable optical attenuator (VOA). All EDFAs have similar optical characteristics, with an output power of 17 dBm and a noise figure of 4.5 dB at an input power of 0 dBm. Then the signal is transmitted through SMF of different lengths. The optical signal filtered through the Bessel optical filter (BOF1) and then it passes through the EDFA and again filtered by BOF2. The two filters have the bandwidth of 10 GHz and depth of 100dB. A photodetector APD is used to convert the optical signal to an electrical signal. A 100 GHz local oscillator has been coupled with a mixer which is linked with electrical signal. The electrical signal is passing through a low pass Bessel filter. The BER analyzer which is connected to the low pass filter will show the eye diagram and detect the BER. Using power meter we have measured the received optical power and the receiver sensitivity. We have studied the BER and Eye-diagrams for different values of SMF length.

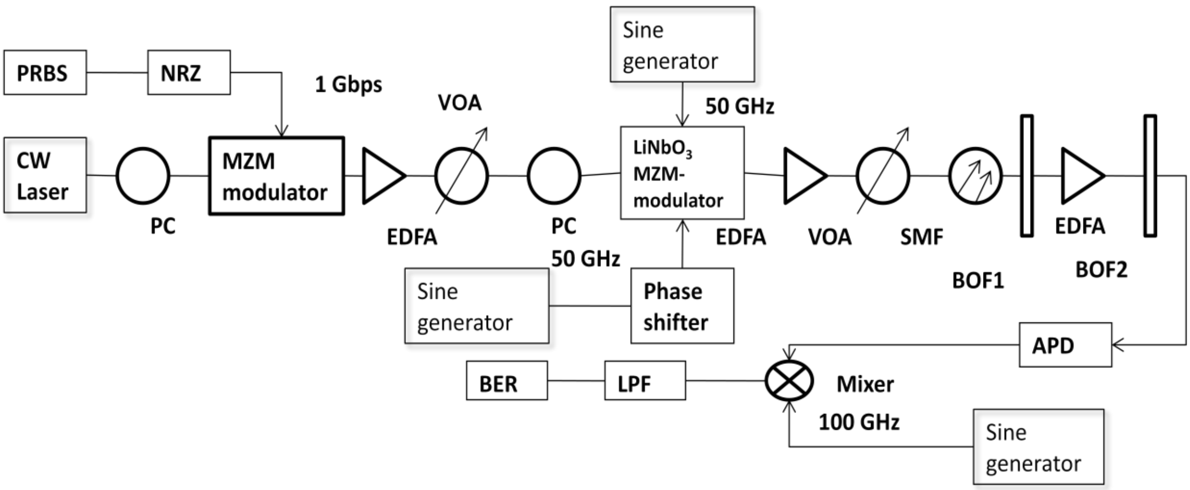
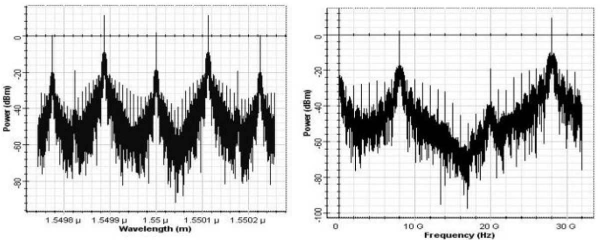


Fig.1. Experimental setup for the generation of optical millimeter wave via external modulation

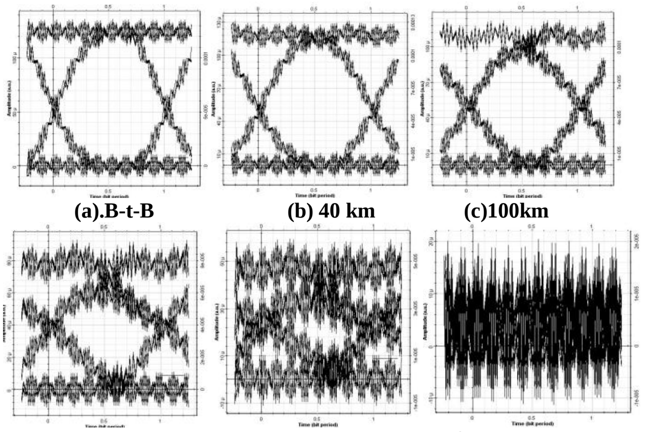
IV. RESULTS & DISCUSSIONS

The transmission of carrier is a waste of power as the information is carried by the sidebands. Furthermore, the carrier suppression also leads to improve the dynamic range and noise figure of the SMF. Fig.2. (a) shows the optical spectrum after the SMF transmission. Fig.2. (b) shows the optical spectrum after receiving and mixed with the clock signal. These optical spectrums at 0 km SMF, suggest that the optical carrier has been suppressed.



(a) (b)

Fig.2. (a) The optical spectrum at transmission end and (b) the optical spectrum at the receiving end (at 0 km SMF)



(a).B-t-B (b) 40 km (c)100km

(d) 140 km (e) 180 km (f) 200 km

Fig.3. Eye diagram at different optical fiber length (a) B-T-B (b) 40km (c) 100km (d) 140km (e)180km and (f) 200km

In the fig.3 eye diagrams of our proposed architecture are shown for the transmission of signal due to the different optical fiber lengths of SMF. The eye diagram of fiber length of 0 km, 40 km, 100 km, 140 Km, 180 Km and 200km are shown in Fig. 3(a), (b), (c), (d), (e), and (f) respectively. These diagrams have clearly shown that the system can transmit 1Gb/s data about 200 km. At 200 km length of SMF the code width is disappeared and the eye is completely closed. The BER is measured by BER analyzer. The signals are built up by the RF component at 50 GHz and superposed onto the DC level. For a BER of 10^{-9}, the receiver sensitivity is 40.2 dBm. The power penalty after 20 km negligible but after 80 km it is almost 2dB. (BER) is defined as the probability of an incorrect identification of a bit by the decision circuit of a receiver [7, 8]. The receiver sensitivity is measured by the minimum average received optical power (P_{min}) required to achieve a fixed BER. If I_d is the decision threshold current the $I_{21}(t) > I_d$, signifies '1'bit is recorded and $I_{20}(t) < I_d$ signifies '0' bit is recorded. Here we suppose $I_{21}(t)$ and $I_{20}(t)$ are the currents in two conditions respectively. Now we have the equation

$$BER = \frac{1}{2}\left[erfc\left(\frac{Q}{\sqrt{2}}\right)\right] \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}} \quad (8)$$

Where Q is the quality factor, and it is represented by

$$Q = \frac{I_{21} - I_{20}}{\sigma_1 + \sigma_0} \quad (9)$$

Now solving for P_{min} we get the equation below

$$Q = \left(\frac{1-r}{1+r}\right)\left(\frac{2RP_{min}}{\sigma_1 + \sigma_0}\right) \quad (10)$$

Where 'r' is extinction ratio and it can be defined as $r = \frac{P_0}{P_1}$. R is the responsivity of the system. From (7) and (8) we can get the relation between BER and the received optical power: $BER \approx KP_{min}e^{-K_1 P_{min}^2}$ (11)

Where $K = \frac{1}{\sqrt{2\pi}}\left(\frac{1-r}{1+r}\right)\frac{2R}{\sigma_1+\sigma_0}$ and $K_1 = \frac{1}{2}\left(\frac{1-r}{1+r}\right)^2\left(\frac{2R}{\sigma_1+\sigma_0}\right)^2$.

The BER is calculated with the help of the eye diagram. As the transmission length approaches towards the, the eye diagram closes gradually. Fig.4 has shown the relation between the BER and the received optical power. The power penalty can be calculated from the figure. The power penalty is defined by

$$\delta = \frac{P_{min}(r)}{P_{min}(0)} = 10log_{10}\left(\frac{1+r}{1-r}\right)dB \quad (12)$$

At the BER of $10^{-9}$the power penalty between 0 km and 100 km transmission length is ~2 dB and for the 0 km and 180 km transmission length it is ~3 dB.

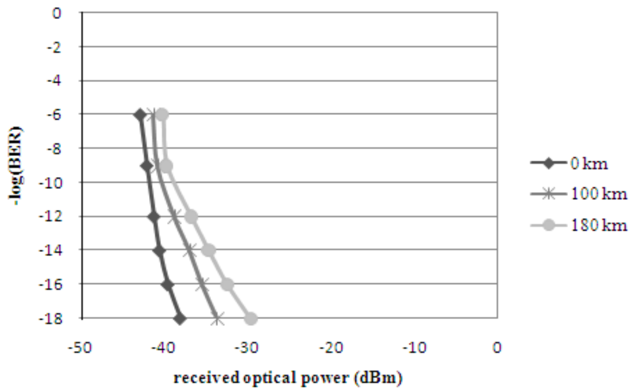


Fig.4. -log (BER) vs. received optical power at different lengths

The received optical powers for the length of 0 km, 40 km, 100 km, 140 km and 180 km are -42.8dBm, -41.9 dBm , -40.7dBm, -40.1 dBm and -39.9 dBm respectively. It is observed that the received power is degraded with the increasing length of the fiber. Fig.5 has clearly shown that the Q-factor is degraded due to increasing length of the fiber. The quality factor is related to the fiber length by the following equation [9]:

$$Q = \frac{(1-r)}{(1+r)}\frac{2RP_{min}e^{-(\alpha L)}}{\sigma_0 + \sigma_1} \quad (13)$$

Where α is the attenuation coefficient and L is the length of the SMF.

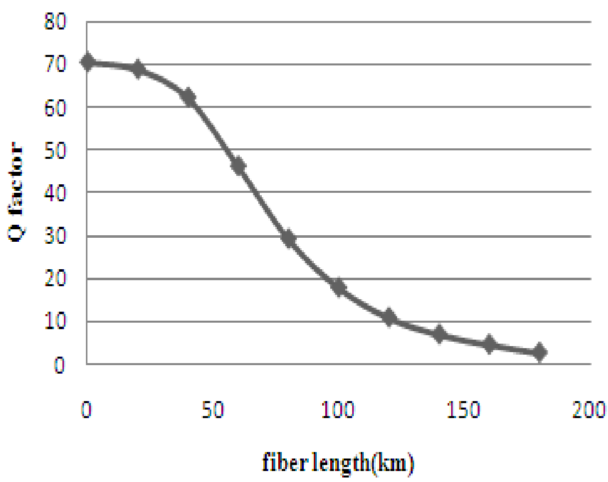


Fig.5. Q factor vs fiber length

V. CONCLUSION

We have theoretically analyzed and observed successfully the generation of the optical millimeter wave by external modulation technique. Since we have used relatively optimized RF signal to drive Li-MZM modulator, the power of the higher order sidebands of the millimeter wave is reduced and the optical carrier is suppressed also. Thus the performance of the system is improved. It becomes more stabilized. The low power penalty shows that this optical network would hardly require any dispersion compensation measure. The relation between the BER and the received optical power has been developed and it is investigated successfully. The eye diagrams clearly suggest that the proposed system is significantly good enough to transmit the 1Gb/s data rate over long-haul SMF. Because of the low power loss, good performance and low cost, the scheme is preferable RoF system for important optical networks like gigabit Ethernet transmissions etc.

ACKNOWLEDGMENT

The authors would like to thank Haldia Institute of Technology and the Science and Engineering Research Board (Under D.S.T), (D.O – SR/ FTP/ PS-092/ 2010, DY NO. SERB/F/2863/2011-2012), Govt. of India, for supporting the research works.

REFERENCES

1. A.Naser, A.Mohamed, A.Rashed, M. Tabour and S.Hanafy " Radio over fiber communication systems over multimode polymer optical fibers for short transmission distances under modulation technique", International Journal of Science and Technology, vol. 1, no. 2, August, 2011, pp. 60-68.
2. R.P.Braun, G.Grosskopf, D.Rohde, "Optical millimeter-wave generation and transmission technologies for mobile technologies for mobile communications, an overview", in: *Proceedings of Microwave Systems Conference, May 1995, IEEE NTC* '9517-19, pp.239.
3. J.Yu, Z.Jia, L.Xu, L.Chen, T.Wang, and G.Chang, "DWDM optical millimeter wave generation for radio over fiber using an optical phase modulator and an optical interleaver", *IEEE photonics technology letters*, vol.18, no.13, 2006, pp. 1418-1420
4. G.Qi, J.Yao, K.Wu, X. Zhang and R. Kasyap ,"Phase-noise analysis of optically generated millimeter wave signals with external modulation technique", *Jounal of Lightwave Technology*, vol. 24, no. 12, Dec. 2006, pp.4861-4875.
5. J.M.Fuster, J. Marti, J.L. Corral, V. Polo and F.Ramos, "Generalized Study of Dispersion-Induced Power Penalty Mitigation Techniques in Millimeter-Wave Fiber-Optic Links". *Journal of Lightwave Technology*, vol. 18, no. 7, July 2000, pp.933-940.
6. G.Smith, D. Novak and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators", *IEEE transactions on microwave theory and techniques*, vol.45, no.8, August 1997, pp.1410-1415.
7. A.O. Aladeloba, A.J. Phillips, M.S. Woolfson, "Improved bit error rate evaluation for optically pre-amplified free-space optical communication systems in turbulent atmosphere", *IET Optoelectronics*, July 2011, pp. 26-33.
8. G.Keiser, *Optical Fiber Communication*, Tata McGraw-Hill., 2010, pp. 269–274.
9. G.P.Agrawal, Fiber-Optic Communication System, John Wiley & sons, inc., publication, 2002, pp. 159-166

AUTHORS PROFILE

Anindya Sundar Das received the M.Tech degree from West Bengal University of Technology, India. Currently he has been working as research fellow in Haldia Institute of Technology, India. His research interest includes passive optical networks using wavelength division multiplexing and components of DWDM.

Banibrata Bag has completed B.E. in Computer Science and Engineering from Burdwan University in 2004 and M.Tech. Under WBUT (West Bengal University of Technology) in 2009. He has worked as a software Developer (from 2005 to 2010), and currently working as an assistant professor (from 2010) in the Dept. of Electronic and Communication Engineering, Haldia Institute of Technology, Haldia, WB, India. His research interest includes networking and Optical fiber communication. He is working towards his Ph.D. degree

Akinchan Das has completed B.Sc. with Electronics (Hons) from Vidyasagar University in 2005, M.Sc. with Electronics from Vidyasagar University in 2007, and M.Tech. with Modern Communication Engineering Under WBUT (West Bengal University of Technology)in 2009.Curently working as an Assistant Professor(from 2010) in the Dept. of Electronic and Communication Engineering, Haldia Institute of Technology, Haldia, WB, India. His research interest includes Wireless networking and Optical fiber communication. He is working towards his Ph.D. degree

Ardhendu Sekhar Patra is working as an Assistant professor at Department of Applied Sciences, Haldia Institute of Technology, Haldia, India. He received his Ph.D. degree from Indian Institute of Technology. He has worked as a post doctorate fellow at Institute of Electro-optical Engineering, National Taipei University of Technology, Taiwan and Center for semiconductor technology and Optoelectronics (ZHO), University of Duisburg-Essen, Duisburg, Germany. His current research interests include the applications of the light-wave communication and WDM-PON systems.