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RESEARCH ARTICLE

FSK signal generation with wavelength reuse capability in 8 Gbit/s radio over fiber systems

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Abstract In this paper, a technique was numerically implemented to generate a frequency shift keying (FSK) radio-over-fiber (RoF) signal in optical domain. Due to the oscillator free generation of FSK signal, this scheme is highly stable with reduced complexity and extremely cost effective. The remote heterodyne detection method was used to detect the signal, where beating occurs to detect the FSK signal. With this scheme, it is able to efficiently generate FSK signal in the range of 60 and 75 GHz at 8 Gbit/s and effectively transmit it over 80 km link without degrading the signal shape and quality. The nonlinear threshold (NLT) point of the system has also been numerically analyzed to estimate the nonlinear tolerance of the system. Besides, the impact of transmission distance and polarization mode dispersion (PMD) was evaluated. Furthermore, the wavelength reuse for the uplink was implemented in the scheme by reusing the same wavelength for uplink that was used for signal generation at downlink. The whole process was performed in optical domain. Thus this scheme is very cost effective as the overall architecture of RoF system is simplified.

Keywords frequency shift keying (FSK), wavelength reuse, transmission parameters, photonic generation

1 Introduction

In the last two decades, it had been shown that there was a tremendous growth in the field of wireless communication industry both in terms of their applications and number of consumers. This enormous growth has no end as everyone wants to be connected anywhere, anytime with anything. Despite of the advantages of wireless networks, they have shortcomings due to lower data rates compared to that offered by the optical fibers in order of Gbit/s. Thus there is an ever-increasing demand to merge both of these technologies [1]. Therefore, radio-over-fiber (RoF) emerges as required. RoF involves the integration of optical fiber link with radio frequency to transfer signals from central station (CS) to remote antenna unit (RAU). For many years, RoF has been developed as a promising technique for wireless broadband functionality. The basic requirement today is to modify and develop low-cost base stations for RoF systems to make them useful for cost-effective placement [2].

Different schemes have been presented and implemented to generate high frequency RoF signals [3–4]. Many of these methods are based on the principle of frequency beating that beat two different signals to shift their spectrum to larger values, but these require electrical oscillators and modulators to generate and modulate these signals. Chi et al. has already proposed an oscillator-free scheme before, which was involved with the shaping of the pulse to produce the modulated signal at output. However, this scheme proposed by Chi et al. has a drawback and the operating frequency cannot be managed fully due to its dependency on dispersive components [5]. Another scheme with photonic signal generation has been reported by Mumtaz et al. [6], but this scheme generated amplitude shift keying (ASK) signal, and ASK is deeply affected by interference and noise. However, frequency shift keying (FSK) is not easily degraded by noise and highly unresponsive to channel instabilities.

Here we proposed a scheme that is free from oscillator and it can generate a high frequency signal that is FSK modulated. Wavelength reuse method was also implemented in this scheme because the wavelength used for signal generation at downlink can easily be re-used for uplink, which simplifies the architecture and reduce cost. On the other hand, frequency doubling obviously requires a pump laser in the configuration to achieve 60 GHz range. So our design is cost effective. Many wavelength reuse methods have been proposed in past like wavelength reuse based on

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injection-locked semiconductor lasers [7], wavelength reuse for upstream data connection [8] uses optical interleaver and wavelength reuse by using single carrier frequency division multiple access (SC-FDMA) in upstream [9]. All of these techniques are efficient in some way, but they were complicated and expensive. Some of these techniques also added noise in the system. The proposed technique in this study is very simple and efficient as single filter and a splitter for reusing are adopted.

In this paper, the signal was generated using remote heterodyne detection method and coherent mixing at the photo-detector. The generated signal was FSK with 60 and 75 GHz frequency band in downlink and reused the wavelength at uplink by splitter. The effects of transmission parameters were also examined by varying physical parameters of transmission both for the uplink and downlink signals.

2 Operating principle

The numerical model of 8 Gbit/s RoF transmission systems is shown in Fig. 1. At downlink, the signal generation occurs as described above. All of this process modulation and coupling is performed at the central station. This generated signal is then transmitted over single mode fiber (SMF). Here we have used 80 km of fiber span length. The data rate is kept constant at 8 Gbit/s. This signal passes through the optical amplifier and splitter in sequence. The splitter has one input and two outputs, which make two copies of the incoming signal, one of them is used in uplink for wavelength reuse and the other is detected at the photo-detector where beating occurs. These steps, i.e., detection and amplification are performed at base station (BS) after which the signal is radiated through antenna. In this scheme, we have also verified that output signal is same as that of input by demodulating the signal.

At uplink side, the wavelength reuse concept is used. For this, a splitter is used at downlink as shown in Fig. 1 that has one input and two outputs. One of the outputs is used for downlink and the other for uplink. The un-modulated continuous wave (CW) Laser 3 is used because the Butterworth Optical Filter, whose bandwidth is properly adjusted, can easily retrieve it. This laser is modulated by Mach Zehnder modulator (MZM), and it is driven by FSK modulated signal that is received from the customer side. The modulated signal is coupled with another CW laser of choice (here we have used 193.2 THz), which causes beating. And an up-converted signal is achieved that can be

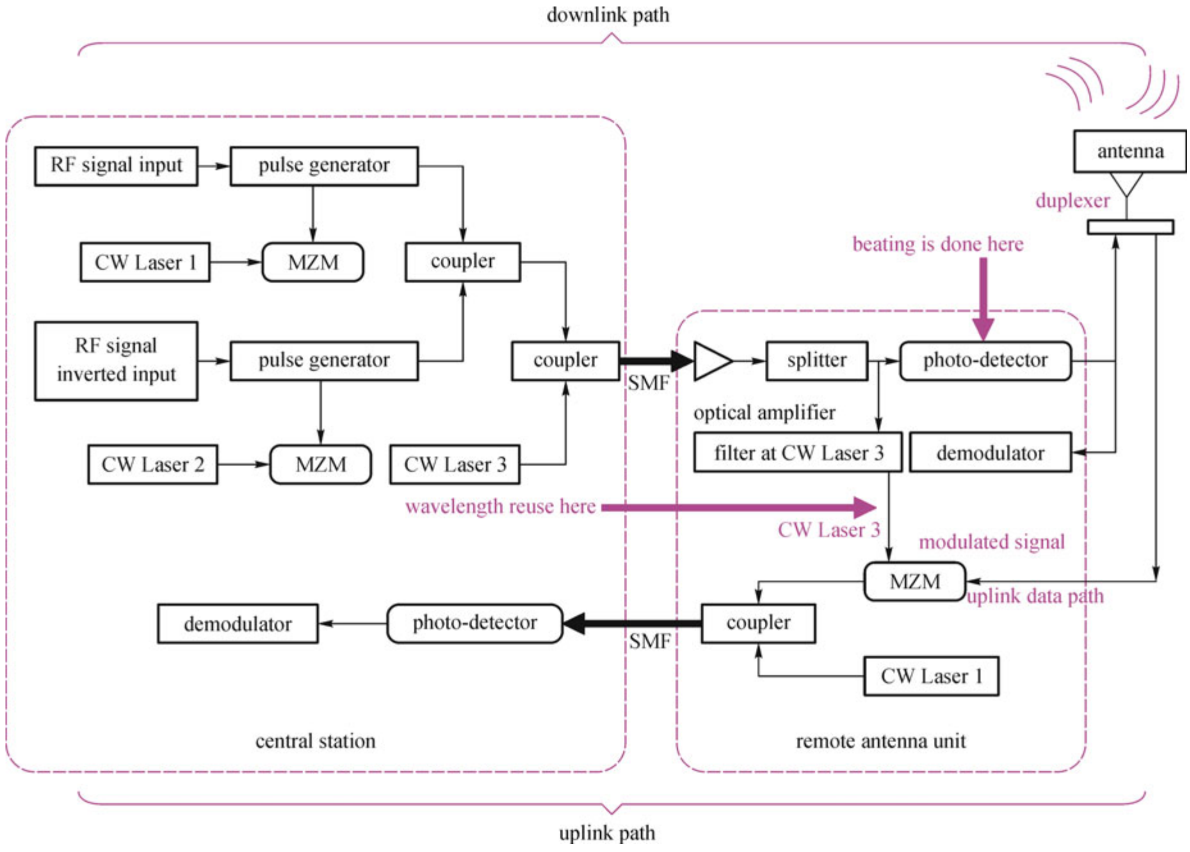

Fig. 1 Block diagram showing proposed solution. RF: radio frequency; CW: continuous wave; MZM: Mach Zehnder modulator; SMF: single mode fiber

easily transmitted. This signal is transmitted through optical fiber and then detected at the photo-detector after amplification.

2.1 Signal generation using remote heterodyne detection

In the proposed system, the remote heterodyne detection method is used, and it works on the principle of coherent signal mixing at the photo-detector to produce radio frequency signals. This scheme is oscillator free and generates the signal in millimeter wave range. In this method, the photodiode also performs as a mixer while doing optical to electrical conversion. Initially two CW laser sources are modulated with the input signal separately using MZM. Laser 1 is modulated with original input signal while Laser 2 is inverted with input signal. As shown in Fig. 2, when input electrical signal is 1 in MZM, it gives the optical signal produced by laser at output; and when it is 0, no signal is generated at the output. However, as inverted signal is used, there is always optical signal at the output with different frequency. Let the Laser 1 signal is A_1 and Laser 2 signal is A_2, the electrical signal input at MZM is 0,1,0,1, and then the output signal is 0, A_1, 0, A_1.

The inverted input electrical signal is 1, 0, 1, 0 and the output signal is A_2, 0, A_2, 0. Both of these signals are combined by the coupler to generate output signal A_2, A_1, A_2, A_1. The third laser is un-modulated and coupled with the modulated optical output from coupler resulting in beating at the detector. The mathematical equations for Laser 1, Laser 2 and Laser 3 with frequencies ω_1, ω_2 and ω_3 respectively are given as below:

$$A_1 = A_{01}\cos(\omega_1 t), \tag{1}$$

$$A_2 = A_{02}\cos(\omega_2 t), \tag{2}$$

$$A_3 = A_{03}\cos(\omega_3 t). \tag{3}$$

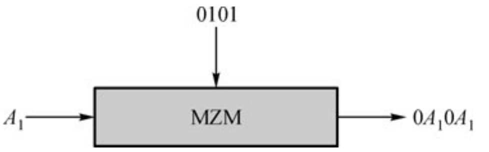

Fig. 2 Modulation of CW laser with RF signal using MZM

When both signals enter a photo-detector, as shown in Fig. 3, the resulting photocurrent is dependent on the square of total of the optical signal fields. When A_1 is at output, the photocurrent in normalized form I_1 will have form as below:

$$I_1 = |A_1 + A_3|^2, \tag{4}$$

$$I_1 = A_{01}A_{03}\cos[(\omega_1 - \omega_3)t] + A_{01}A_{03}\cos[(\omega_1 + \omega_3)t] + \text{other terms}. \tag{5}$$

When A_2 is at output, the resulting photocurrent I_2 is as below:

$$I_2 = |A_2 + A_3|^2, \tag{6}$$

$$I_2 = A_{02}A_{03}\cos[(\omega_2 - \omega_3)t] + A_{02}A_{03}\cos[(\omega_2 + \omega_3)t] + \text{other terms}. \tag{7}$$

The terms we are interested in are: $A_{01}A_{03}\cos[(\omega_1 - \omega_3)t]$ in case of A_1 output, and $A_{02}A_{03}\cos[(\omega_2 - \omega_3)t]$ in case of A_2. The rest of the terms are ignored and filtered out by photodiode indicating that by properly monitoring the difference of frequencies between the two signals. The radio signals of any frequency can be produced.

Due to the bandwidth inadequacy, the frequency of generated signal has limitations. The binary FSK signal is

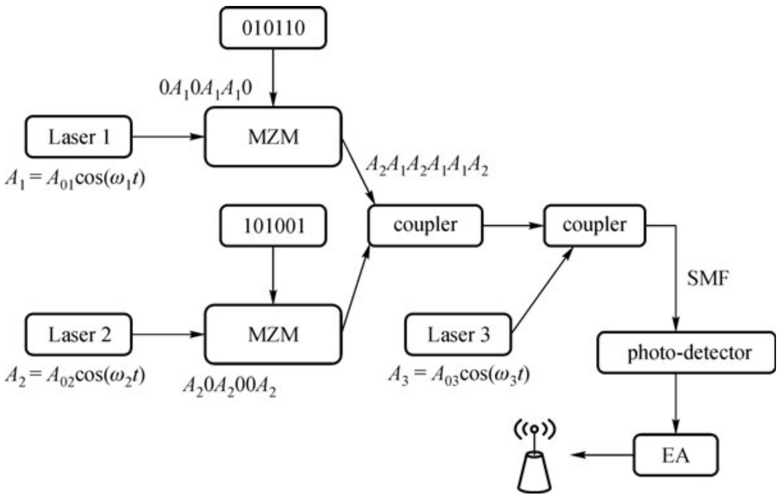

Fig. 3 Block diagram for signal generation by optical heterodyning. EA: electronic amplifier, SMF: single mode fiber, MZM: Mach-Zehnder modulator

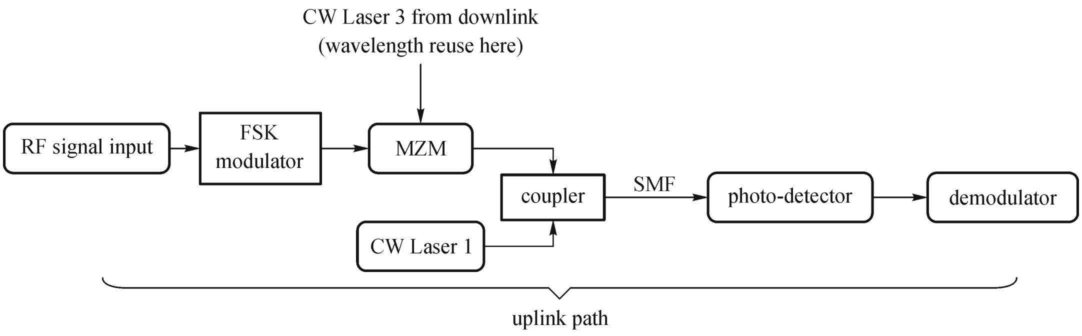

Fig. 4 Uplink path of proposed scheme

generated by this method with frequencies $f_1 = \omega_1 - \omega_3$ and $f_2 = \omega_2 - \omega_3$. The frequency-modulated signal is then received and provided to antenna using amplifier at remote station. This scheme has proficiency to animatedly vary its frequency by changing the wavelength of Laser 3. All of the modulation and generation occur at the centralized office, and the base station simply detects the coming signal and transmits it to remote stations after amplification. The whole modulation is finished in optical domain, and there is no need to do modulation at base station. The wavelength of Laser 1 is set to 1551.72 nm whereas the wavelength of Laser 3 is 1552.21 nm in the schematics. The signal is combined into fiber by using a coupler. The spectrum of combined signal has two signals that are closely spaced with spacing of about 0.49 nm which is almost 60 GHz by using formula $\Delta f = (c/\lambda^2)\Delta\lambda$. Similarly, the Laser 2 has wavelength of 1551.60 nm whereas Laser 3 has wavelength of 1552.21 nm. After coupling, the spectrum of combined signal has separation of approximately 0.61 nm, which is almost 75 GHz. Thus, by properly managing the frequency spacing between the lasers different high frequency signals can be generated.

2.2 Implementing wavelength reuse at uplink

The un-modulated CW Laser 3 is received from the splitter by filtering at the laser frequency at uplink, as shown in Fig. 4. This is modulated with the signal coming from customer side by MZM, and then it is coupled with any laser source of your choice. The photo-detector detects this signal, of which frequency is different between two laser sources.

3 Simulation results and discussion

The simulation setup is developed in OptiSystem v11.0 software and the results are analyzed in MATLAB. Signal generation is performed at downlink by using three CW laser sources. The bit-rate is kept constant to 8 Gbit/s. The signals are monitored at the time domain visualizers. Figure 5 shows the original input signal and Fig. 6 shows the inverted signal which clarifies that for normal signal where there are 1's, the inverted has 0' there and vice versa.

Using this technique data can be efficiently transmitted upto 80 km standard single mode fiber length at downlink and generate the signal of 60 and 75 GHz shown in Fig. 7. But this scheme is flexible in terms of output frequency, which is changed with the frequency of three lasers. The results depict the two prominent peaks at the previously mentioned frequencies. From the results, we have also seen that these peak frequencies are least effected the fiber transmission impairments. The resultant generated FSK signal at the receiver is shown in Fig. 8.

The eye diagram is depicted in Fig. 9 that indicates a good eye-opening and very little distortion. It is clear from the eye-diagram that in our proposed scheme, timing jitter is minimized and we have obtained a very clear eye-opening. Due to this reason, this scheme can be used for longer transmission distances on SMF, where linear and non-linear fiber impairments are the main degrading factors. Figure 10 depicts the demodulated signal after

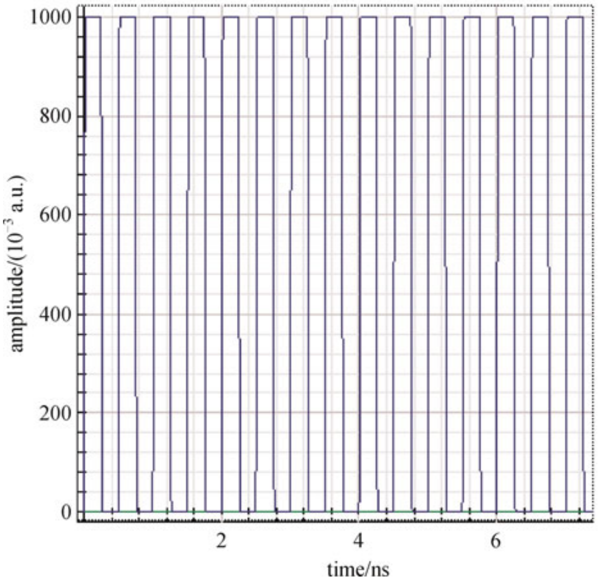

Fig. 5 Original input signal

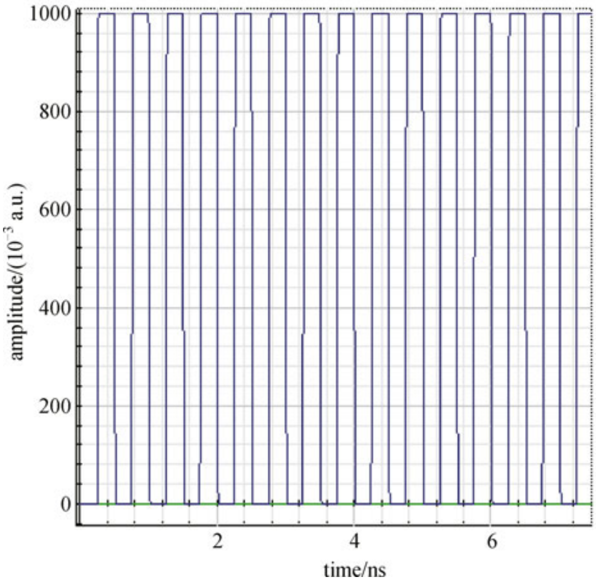

Fig. 6 Inverted input signal

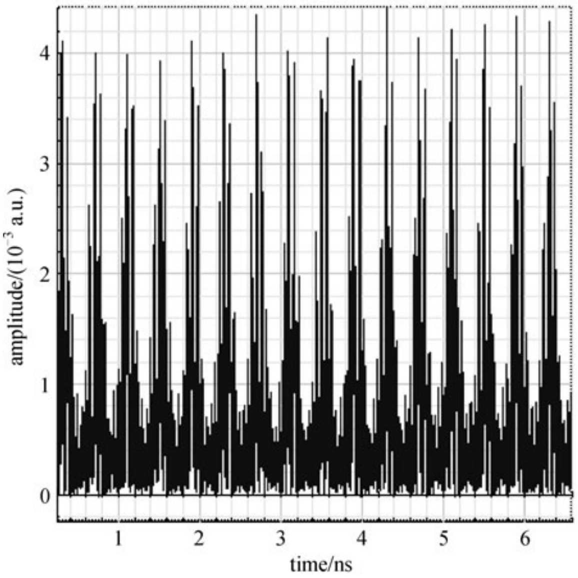

Fig. 8 Generated FSK signal at photo-detector

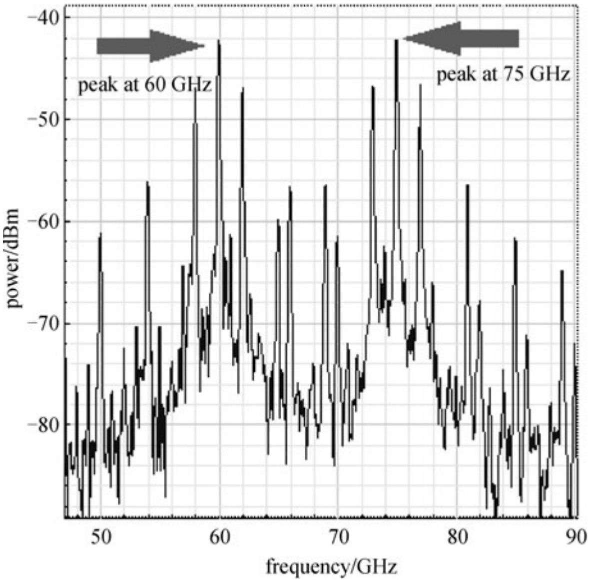

Fig. 7 Spectrum output of photo-detector at downlink

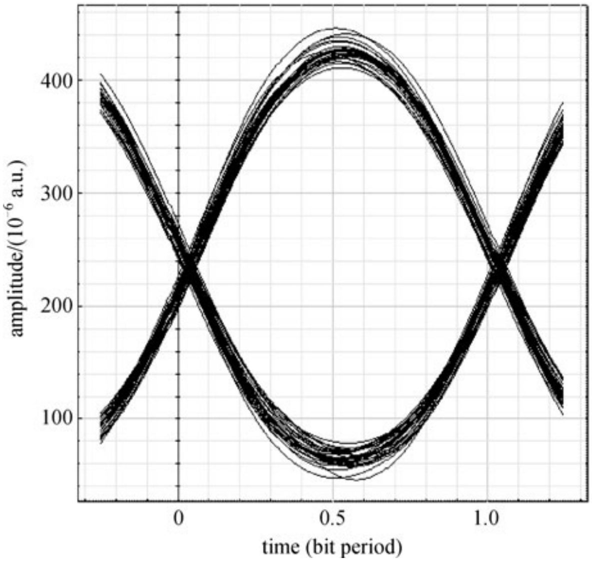

Fig. 9 Eye diagram

coherent detection, which verifies the same signal as the input bit sequence above in Fig. 5.

3.1 Trends observed by varying transmission parameters at downlink

The impact of different physical transmission parameters on the performance of RoF systems is analyzed in this section. We have analyzed the system by varying input power from – 10 to 20 dBm and keeping bitrate constant to 8 Gbit/s and distance 80 km. The graph in Fig. 11 shows that at lower launch powers the system performance is improved and we have not seen any significant impact of fiber transmission impairments. Whereas at higher launch powers, i.e., 9 dBm and above the non-linear fiber impairments, self-phase modulation, significantly degrades the transmission performance. Figure 11 shows the nonlinear threshold (NLT) point is at 9 dBm, and at the beginning with the increase of input power the bit error rate (BER) values have shown efficient transmission performance. But at NLT point at approximately 9 dBm, the improvement in system performance saturates and

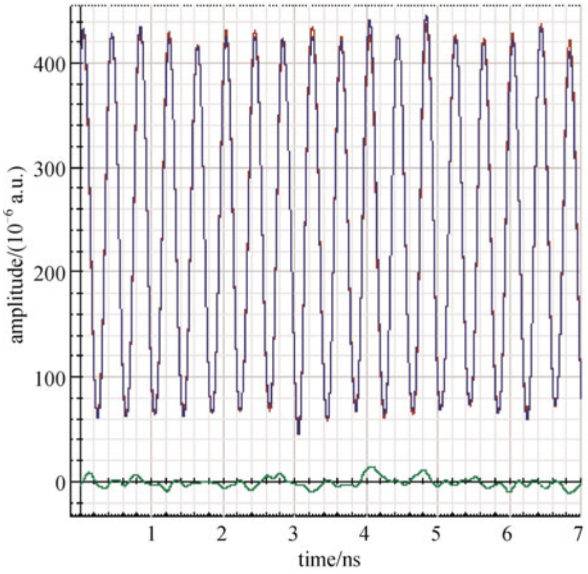

Fig. 10 Demodulated output

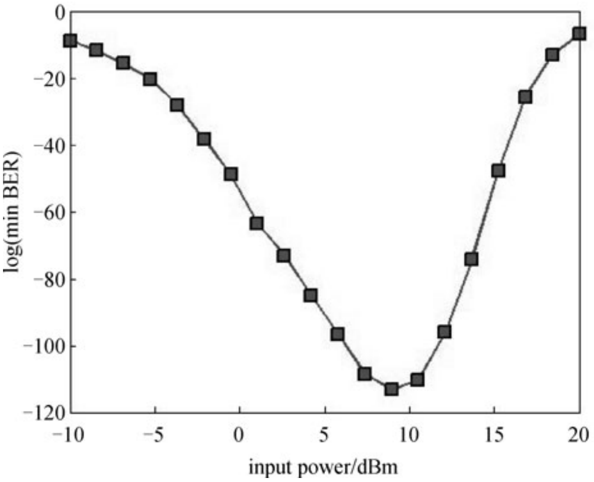

Fig. 11 Change in BER by varying input power

nonlinearities dominates. After that point, the transmission performance gets worst, which is evident from the BER values.

In the next analysis, the distance was increased from 10 to 200 km, while the power was kept constant at 9 dBm and bitrate was 8 Gbit/s. As shown in Fig. 12, the BER value increases with transmission distance, as a result of losses, signal distortion and fiber linear and non-linear transmission impairments. By properly placing the amplifiers and adjusting their gains, the power losses can be compensated. Whereas, the fiber transmission effects can be compensated with the help of digital signal processing and digital filtering at the coherent receiver.

Furthermore, the impact of polarization mode dispersion

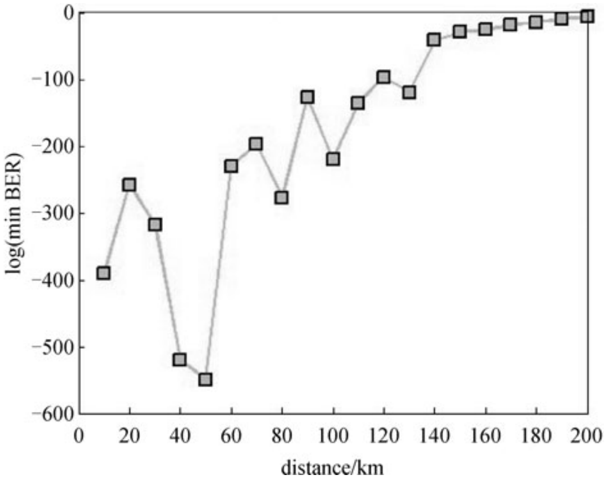

Fig. 12 Change in BER by varying transmission distance

(PMD) was also quantified. The results are depicted in Fig. 13. By increasing the PMD value of the fiber from 0.05 to 0.50 ps/sqrt(km) at 13 dBm input power, 80 km distance and bitrate 8 Gbit/s, it was found that with increase of the values of PMD, the system performance degrades. As PMD is a stochastic process, complex signal processing techniques are required along with coherent receivers to compensate the impairment.

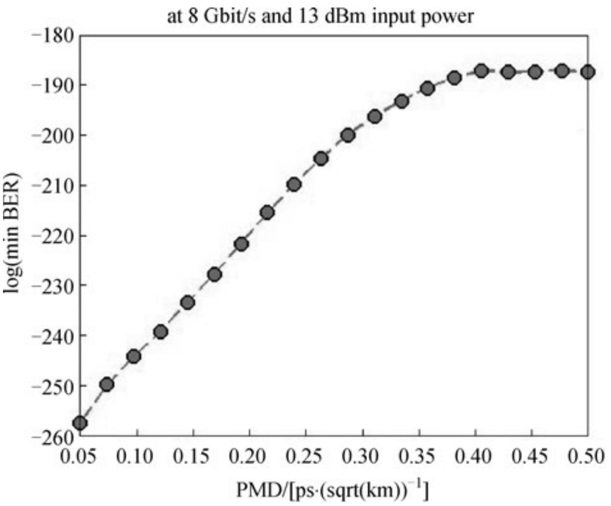

Fig. 13 Change in BER by varying PMD

A comparison was also made by varying the input power from −10 to 20 dBm keeping distance constant at 80 km with different bitrates. Figure 14 depicts that as the bitrate increases the fiber transmission impairments degrades the transmission performance. The point of nonlinear threshold also shifts toward lower power values as the bit-rate increases, which are evident from 9 and 12 Gbit/s. The nonlinear threshold for 8 Gbit/s is at 9 dBm, for 9 and

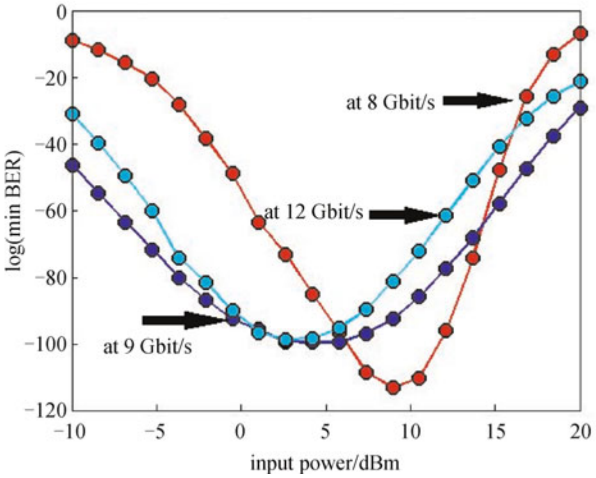

Fig. 14 Change in BER by varying input power at different bitrates

12 Gbit/s it is at 4 and 2 dBm signal launch power respectively.

3.2 Analysis of wavelength reuse at uplink

The proposed scheme is capable of transmitting data efficiently up to 25 km by reusing the laser source, which is used for downlink signal generation. The input for the laser, received from downlink, is of good power and can be efficiently used in uplink resulting in minimum BER. Figure 15 shows the input signal at uplink, and Fig. 16 is the output signal that verifies almost the same signals with very small distortion that is due to signal distortion in the system.

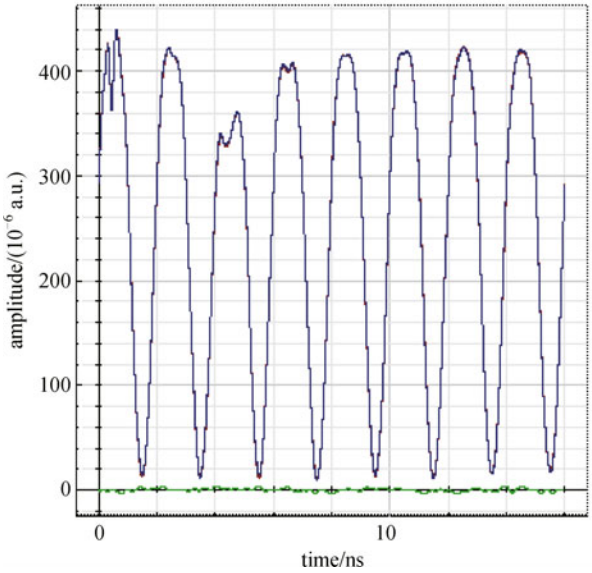

Fig. 16 Output signal after demodulation

As a result of the beating of two CW lasers, the signal produced at photo-detector have the frequencies that is different between two laser sources, i.e., here the frequency is 193.20 THz – 193.14 THZ = 60 GHz, as shown in Fig. 17. Moreover, the output of band distortions can further be suppressed by using the digital filters. The respective eye diagram is also given in Fig. 18 that shows a good eye-opening, also depicting good signal quality for wavelength reuse.

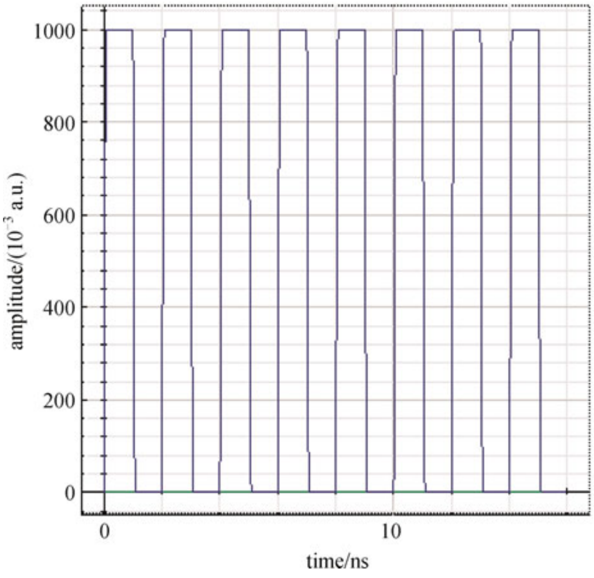

Fig. 15 Input signal for uplink

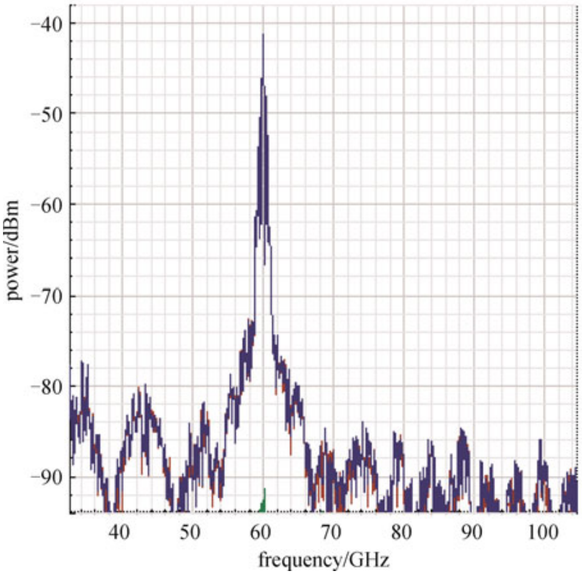

Fig. 17 Spectrum at output showing peak at 60 GHz

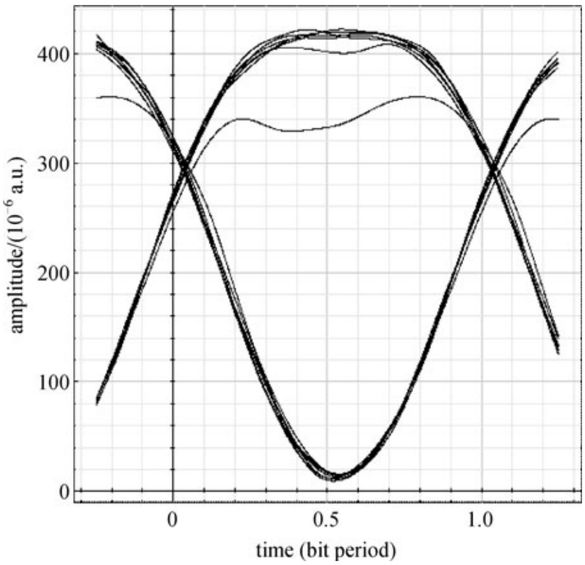

Fig. 18 Eye diagram for uplink output signal

3.3 Trends observed by varying transmission parameters at uplink

The impact of signal launch was analyzed for the uplink, as depicted in Fig. 19. The trend was studied by varying the input power from -15 to 15 dBm. The distance is kept constant at 25 km of SMF. The NLT point is at 6 dBm, nonlinearities become dominant with BER value increases. This system show irregular behavior and error rate starts increasing.

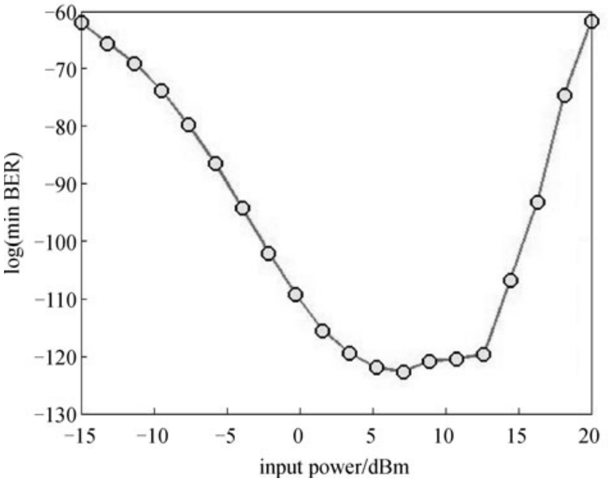

Fig. 19 Trend in bit error rate by varying input power at 25 km

Another finding is the distance ranged from 0 to 50 km, the power was kept constant at 6 dBm. The results are shown in Fig. 20. The general trend is the BER gets worst by increasing the distance, which is due to the fiber linear and non-linear transmission impairments. Also there was distortion due to errors and power losses in the system. The system performance for uplink can further be improved by using the digital signal processing techniques such as finite impulse response filter or non-linear compensation through split-step Fourier methods. These techniques will compensate the chromatic dispersion and the non-linear effects of the fiber transmission resulting in improved non-linear threshold point as well as greater transmission distances.

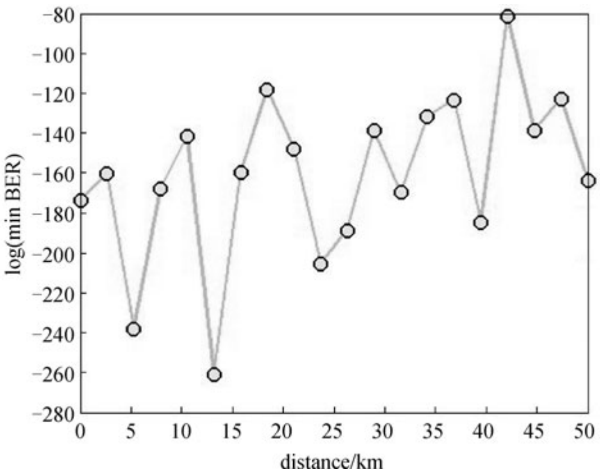

Fig. 20 Trend in BER by changing transmission distance

4 Conclusions

The proposed scheme includes a complete, stable and economical design of a RoF system to support very high data rates. It is stable due to the limitations of electrical components analog-to-digital converters (ADCs), and higher data rates in this scheme are no more a problem. At downlink, the signals of 60 and 75 GHz were successfully generated and can be transmitted up to distance of 80 km at 8 Gbit/s. It was observed that the best results were obtained at 9 dBm power level. The BER analysis suggests that RoF system can support high data rates with negligible losses. For uplink, it was possible that at 6 dBm power, signal can be transmitted efficiently up to 25 km distance. The uplink of proposed scheme utilized wavelength reuse method, which can simplify the design of BS because the quantity of lasers is lessen, but the optical amplifier positioning and gain settings are the basic requirements. Further improvements can be done to implement this method in prevailing RoF network architectures, ultra-wide band (UWB) radio applications and next generation optical systems to confirm the compatibility of the proposed model.

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