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Performance Analysis of Optical Frequency Multiplication Based Bi-Directional Rof using FPI

Rajesh

***Abstract:** A cost-effective novel method, Optical Frequency Multiplication using a Fabry Parot Interferometer (FPI), is demonstrated with Optisystem for generating micro/ millimeter signals optically and distributed to several remote located base stations. The simulation results show that the relative strength and frequency of the harmonics is strongly dependent on sweep frequency, FSR, Frequency Deviation and FM index. It is observed that optical uplifting of 150 Mbps AM radio signals to 11.8, 17.8 and 23.8 GHz frequencies corresponding to 4^{th}, 6^{th} and 8^{th} harmonic after transmission in optical downlink with the power level of 10 dbm, -10 dbm and -20 dbm respectively. Similarly, ASK data is recovered from the 4^{th} harmonic of 12 GHz. To down-convert the uplink AM-RF signal of 5.8 GHz to a low IF of 200 MHz, 6 GHz high-frequency carrier generated by OFM is used, which is then sent back to the Central Station. QAM data at 550 MHz subcarrier is also recovered at CS successfully from 4^{th} harmonic. Hence, the OFM system is used successfully for multiple functions concurrently, such as high-frequency-carrier-generation, optical signal transportation, frequency up-conversion, and bi-directional data transmission through generated harmonics.*

***Keywords:** ASK, FPI, FSR, MZM, QAM.*

I. INTRODUCTION

Next-generation wireless networks must provide high broadband access, which can be possible by integrating the two different technologies, the fiber optics and wireless communication. The bandwidth requirements of consumers are increasing tremendously that is motivated by bandwidth hungry applications including High-Definition TV (HDTV), IP Television (IPTV), Video-Conferencing, Video on Demand (VoD), Live-Streaming, Telemedicine, Voice over IP (VoIP) and many more. They require very high-speed data transmission to fulfill such types of demand of the consumers. It can be possible only by providing the optical fiber closer to the consumer premises that offers enormous bandwidth. In addition, this increasing demand for more and more bandwidth must be provided via wireless access networks. RoF (Radio-over-Fiber) technology is an appropriate means to construct a hybrid network of fiber optics and wireless access that enables seamless integration of both types of infrastructures [1].

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***** Correspondence Author
Rajesh*, Project Manager, Haryana State Electronics Development Corporation (HARTRON), Panchkula-134109, Haryana, India

The realization of integrated optical/ wireless networks supports current and future capacity demands effectively and reliably in a cost-effective manner. The growing data rates, emerging new services and advanced multiple wireless standards are putting up pressure on RoF to face the new challenges and opportunities presenting by a new era of technologies.

In RoF, to reduce the complexity and cost of the Base Station (BS), electrical and optical components which are used for the different processing functions namely RF generation, multiplexing, coding and modulation, are to be shifted to the Central Station (CS), jointly shared by a large number of Base Stations (BS) [2-3].

Today, a variety of methods can be used to generate and transmit radio frequency signals optically, but, IM/DD is extensively used because of its inherent easiness. In this technique, the radio frequency signal modulates the light source directly and transmitted to the BS through optical fiber media. CW-LD either modulated directly or by employing an external modulator (Electro-Absorption Modulator/ Mach-Zehnder Modulator).

The optical generation of radio frequency signals in micro-millimetre range is the hot topic that demands added attention of the research scholars today. The two most popular ways to generate optical microwave carrier are Remote Heterodyne Detection (RHD) and the generation of harmonics optically. Basic principle of RHD is coherent mixing of two carries in the photo detector for generating the RF signal [4] and the frequency drift between these two carriers generated by master-slave Laser Diodes produces the wanted radio frequency signal. The simple configuration, the possibility of generation of carrier of very high-frequency with low RF signal, insensitive to chromatic dispersion and above all low cost are the main advantages of this technique. The limited bandwidth of the PD, the requirement of complex optical filters, and unstable carrier because of variable laser phase noise are the bottlenecks to the other side. To cater all these bottlenecks, the additional mechanism to control phases like Optical Injection Locking (OIL) and Optical Phase Locked Loops (OPLL), are required to attain high quality and highly stable carrier that increases the complexity of the system. The second method for the generation of highly stable harmonics of high-frequency is Optical Frequency Multiplication (OFM) which is a very simple and economical method [5, 9-10]. A large number of techniques based on OFM principal are used today.

For example generation of harmonic using single modulator [6], generation of harmonic using cascaded modulators (MZMs/ EAs) [7-8], generation of harmonic using modulator with interferometer (MZI/ FPI) [9-11], generation of harmonic using optical phase modulator (PM), generation of harmonic using Optical Carrier Suppression (OCS) [12-13], Frequency Up-lifting by Optical Amplifier [14-15], FM/ PM with interferometer [16], Four-Wave Mixing [17], and many more.

The proposed bidirectional RoF link based on OFM principal is represented in Figure-1. A n optical transmission downlink consists of CW laser source, frequency modulator, MZM modulator, FPI and semiconductor amplifier at Central Station (CS) and a remote generation of LO at the Base Station (BS). In a similar way, RF uplink signals remotely down-converted for uplink transmission, in which Intensity Modulation (IM) is used at the BS and detection of the light at the CS direct. At the Central Station, the light source λ_{DL} is FM modulated in downlink by a sweep signal of frequency f_{sw} and then a Fabry Perot Interferometer (FPI) is used to pass this modulated signal. The downlink data which is composed of a subcarrier $f_{\mathrm{sc-DL}}$ modulates the intensity of this frequency-swept optical signal. The frequency of subcarriers $f_{\mathrm{sc-DL}}$ should be lower than $f_{\mathrm{sw}}/2$, to avoid crossing the maximum limit of RF bandwidth permitted by the OFM method. The ensuing optical signal is then transmitted to the optical fiber and retrieved with the help of photo detector at the remotely placed base station.

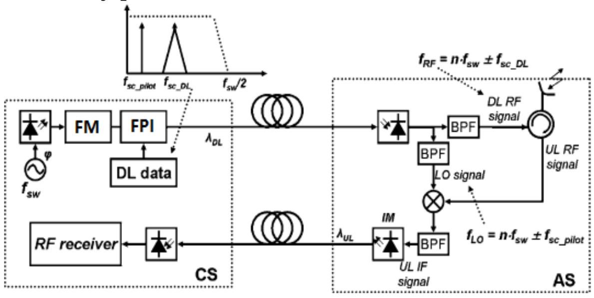


Fig.-1: Bidirectional RoF link employing OFM

The different radio frequency harmonics which are spaced by the sweep frequency f_{sw} are obtained at the output of the photo detector. The relative amplitudes of all these components are depending on sweep frequency (f_{sw}), the Free Spectral Range (FSR) of the FPI and the FM index. Besides harmonics, the subcarriers $f_{\mathrm{sc-DL}}$ are up-converted to $f_{RF} = n.\ f_{sw} \pm f_{sc-DL}$ at the CS, where n represented the n^{th} harmonic of fundamental sweep frequency. The preferred f_{RF} signal can be chosen with an appropriate bandpass filter and transmitted to the antenna for downlink transmission. Similarly, the preferred LO (f_{LO}) is chosen with another appropriate bandpass filter and used as a LO at the base station. The RF signal which is coming for uplink transmission is mixed with the selected f_{LO}. The intensity of the uplink light source λ_{UL} is modulated directly by the uplink IF signal at $f_{\mathrm{sc-UL}}$, and returned back through the media of optical fiber to the CS. At the CS, it is retrieved by direct detection and further processed by the RF receiver.

II. SIMULATION AND RESULTS

A. Downlink transmission- Amplitude Modulation

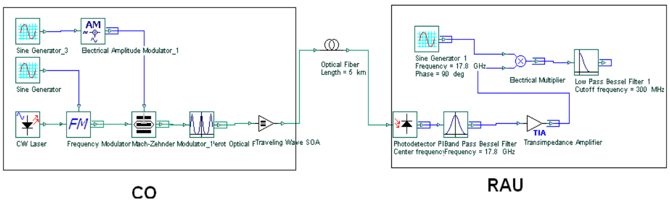
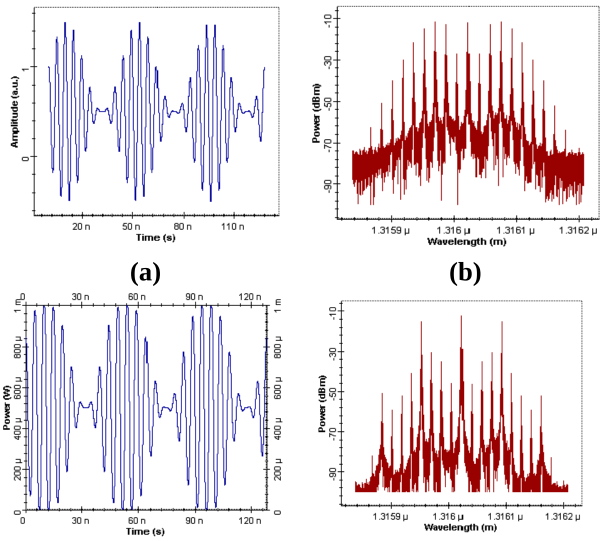


Fig.-2: System Set-Up for Microwave Carrier Up-Conversion and AM Data Modulation

Figure-2 shows the system set-up which is used for generating the Amplitude Modulated signal. An external modulator of MZM type is placed just after the Frequency modulator in this experiment, but it can also be put up in front of the FM modulator. It means that the functions of FM and IM are mutually changeable. The DFB laser output set at 1316.02206302 nm to achieve the frequency of 227.802 THz to align properly with the FPI filter that has the FSR of 12 GHz. The power and line-width of the laser is 0dbm and 2 MHz respectively. The swept signal frequency is 3 GHz and the peak to peak frequency deviation of the FM modulator is set to 24 GHz to achieve the multiplication factor of four. The responsivity of the photo detector is 0.9A/W. The 200 MHz modulated carrier with 20MHz modulating signal is fed to the MZM modulator.



(a) (b)

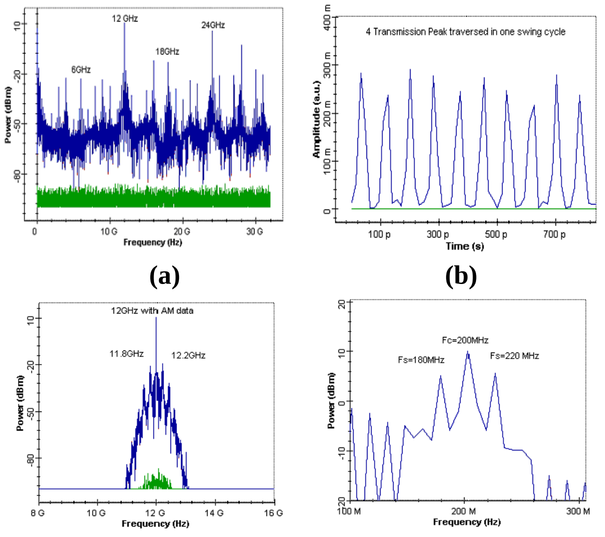
(c) (d)

Fig.-3: (a) Amplitude modulated signal (b) The spectrum of the MZM optical modulator output (c) AM signal at MZM output (d) The spectrum at the output of FPI filter.

Figure-3 shows the outputs of all the components used in the system set up at the Central Station. Figure-3(a) shows the amplitude modulated signal and their spectrum at the output of electrical AM modulator. The output of the Electro-Optic FM modulator has the sidebands centered on the 1316 nm optical carrier at a spacing equal to the sweep signal frequency of 3GHz.

The sinusoidal swept optical carrier is modulated with AM signal at MZM optical modulator.

The spectrum and the output of the MZM modulator are shown in figure-3(b) & figure-3(c). Figure-3(d) shows the output of the FPI filter.

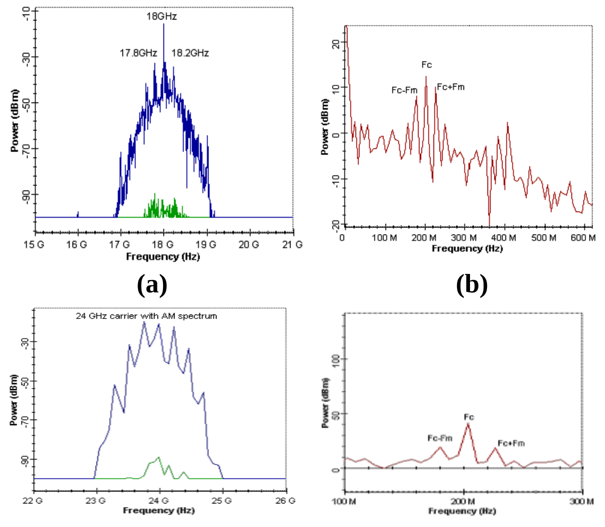


(a) (b)

(c) (d)

Fig. 4(a) The photodiode output spectrum with AM (b) Time plot of the detected electrical signal at RAU (c) BPF output 12 GHz carrier with AM (d) AM spectrum recovered from 4th harmonic.

At the RAU, photodiode converts the optical carrier into an electrical signal. At the output of the photodiode, the basic fundamental frequency and their harmonics are available with AM signal. Now, it is our choice that from which harmonic AM signal will be recovered. The bandpass filter centered at 12 GHz is used to recover the signal from 4th harmonic. It has two sidebands at 11.8 GHz and 12.2 GHz, which clearly shows the AM signal at 200 MHz subcarrier frequency with 20 MHz modulating signal as shown in figure-4(c). Figure-4(d) shows the frequency spectrum of the AM modulated carrier generated by OFM.



(a) (b)

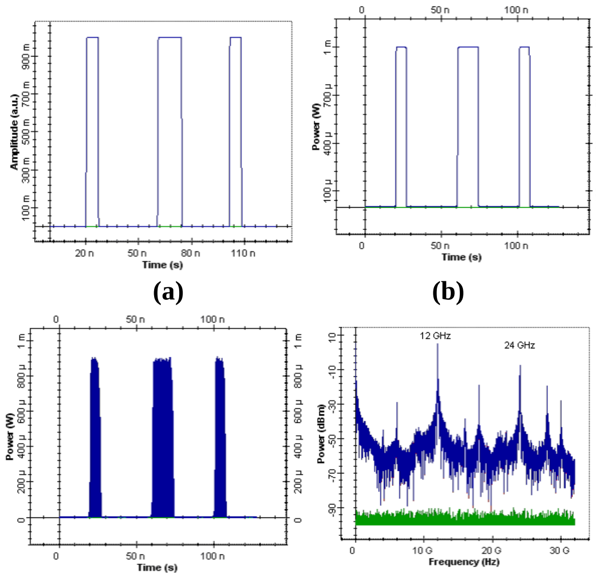
(c) (d)

Fig.-5: (a) 6th Harmonic of 18 GHz with AM signal (b) AM spectrum recovered from 6th Harmonic (c) 8th harmonic of 24 GHz with AM signal (d) AM spectrum recovered from 8th Harmonic

With the help of an appropriate filter, we can select any harmonic to transmit data to the wireless channel as every harmonic contains the AM modulated data. In this simulation, 4th, 6th and 8th harmonics are used to transmit the data in downlink path. Figure-5(a) & figure-5(b) show the filtered 6th harmonic that has AM subcarrier and recovered AM spectrum respectively. Similarly, figure-5(c) & figure-5(d) show the 8th harmonic with AM signal and recovered spectrum of AM respectively. With this harmonic carrier, data is to be transmitted to the wireless channel.

B. ASK data Modulation

To generate Amplitude Shift Keying (ASK) or On-Off Keying (OOK) modulated microwave carrier, baseband data is used to drive the MZM modulator. The amplitude and bias are adjusted so as to produce an electrical signal with a sufficient modulation depth at the photodiode.



(a) (b)

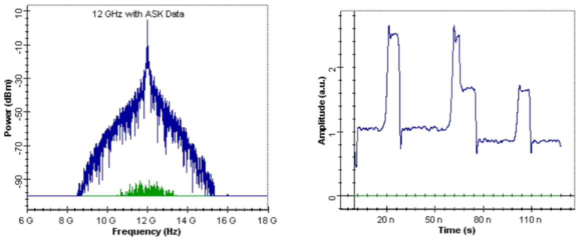
(c) (d)

Fig.-6: ASK data modulation on 4th harmonic carrier (a) 150 Mbps NRZ data (b) MZM modulator output with OTDR (c) FPI filter output with ASK (d) photodiode output spectrum with ASK data.

The PRBS generator is used to obtain the ASK modulation. The data rate of the PRBS is set to 150 Mbps. The signal leaving the MZM is intensity-modulated in addition to the FM modulation performed on it earlier. This is confirmed by the generated electrical signal at the photo detector. The frequency spectrum of the photo detector shows that all the generated carriers are modulated by the PRBS data, and therefore any of them may be used for radio transmission.

Figure-6(a) shows the NRZ pattern of 150 Mbps data. The output of MZM modulator in the time domain is observed with an optical time domain visualizer that modulates the optical carrier with NRZ data shown in figure-6(b). The output of FPI periodic filter is shown in figure-6(c). Figure-6(d) shows the photo detector output spectrum with ASK data.

The electrical signal is filtered using wideband BPFs centered on 12 GHz as shown in figure-7. To recover the transmitted data, a coherent detector using a LO operating at the appropriate frequency i.e. 12 GHz in our experiment, has been used. The maximum data rate that can be transmitted is determined by the factor such as whether the data is pre-filtered to reduce the roll-off, the kind of data being transmitted (RZ or NRZ), and so on. However, the upper limit of the data rate of the available bandwidth for data transmission is determined by the sweep signal frequency, the bandwidth of the Mixer and filter.



(a) **(b)**

Fig.-7: (a) Spectrum of the 12 GHz BPF filtered NRZ modulated microwave signal (b) Time plot of the data recovered from the 12GHz microwave carrier.

III. UPLINK TRANSMISSION

It is confirmed that high-frequency microwave signals can be generated and transmitted to remote antenna unit by using OFM technique successfully through a media of optical fiber. It may be single mode or multimode. The recovered microwave harmonics have outstanding quality with low phase noise. Therefore, these microwave harmonics signals may also be used for uplink transmission in a novel and economic way. Any harmonic component may be chosen with the help of an adequate bandpass filter which can be used as a LO to down-convert the uplink signal coming from the wireless terminal to an IF frequency. Because of this down-converted low frequency IF signal, the cost of the LED and FP lasers decreases tremendously for uplink resulting in simple and cost-effective RAU.

A. AM Modulation

The simulation set-up for generating AM data for the uplink transmission is shown in Figure-8. The head end is essentially the same as the one used for DL with the addition of receiving part of the system.

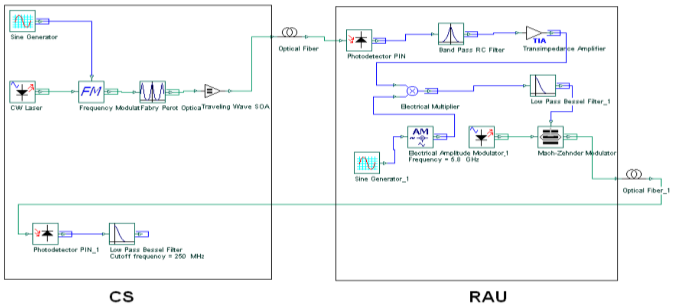
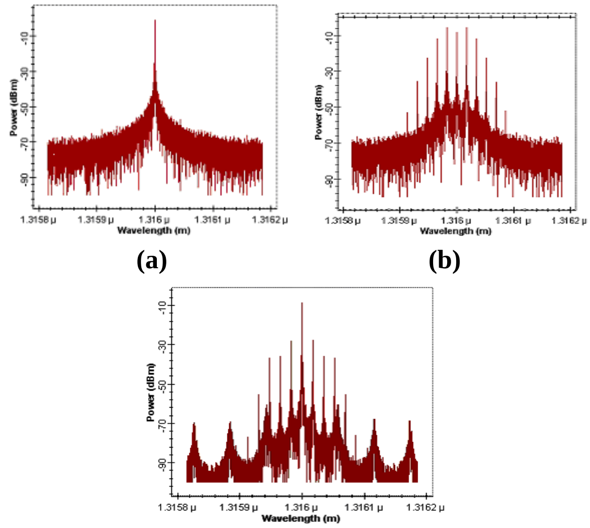


Fig.-8: System set up for uplink transmission.

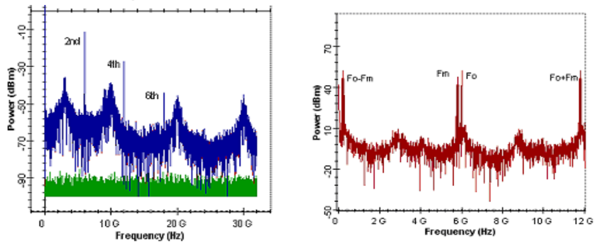
The high-frequency radio signals coming from wireless users are needed to down-convert before transmitting to the optical fiber to overcome the fiber chromatic dispersion effects. The Optical Frequency Multiplication technique is used for down-conversion and to avoid the RAU hardware complexities. Instead of using the separate local oscillator at RAU, the OFM generated harmonic is used as LO. As in DL, the 3GHz frequency is swept with a frequency modulator on the 1316 nm optical signal of CW laser and a frequency deviation of 15 GHz is used. The FPI filter is used as a periodic filter for the optical frequency multiplication. The Free Spectral Range (FSR) of the FPI is 12 GHz. Figure-9(a) shows the spectrum of CW laser at 1316nm and is applied to the FM modulator. The 3 GHz swept the optical spectrum shown in figure-4.9(b). It shows the harmonics placed at 3GHz spacing. The optically multiplied spectrum produced by FPI shown in figure-9(c).



(c)

Fig.-9: Uplink transmission of AM signal (a) 1316 nm Laser output spectrum (b) 3GHz swept FM output spectrum (c) FPI filter output spectrum.

Figure-10 shows the RF spectrum at the remote antenna unit. OFM generated $2^{nd,}$ 4^{th} & 6^{th} harmonic at 6 GHz, 12 GHz & 18 GHz respectively are shown in figure-10(a). For the uplink transmission experiment, 2^{nd} harmonic of 6GHz has been used as a LO. It is filtered with a Bessel bandpass filter with a center frequency of 6 GHz. The 5.8 GHz carriers with AM signal came from the wireless channel to transmit in the uplink direction. To down-convert this signal, the carrier is mixed with recovered 2^{nd} harmonic of 6 GHz LO. The mixer generates the inter-modulation terms of these two frequencies as shown in figure-10(b).

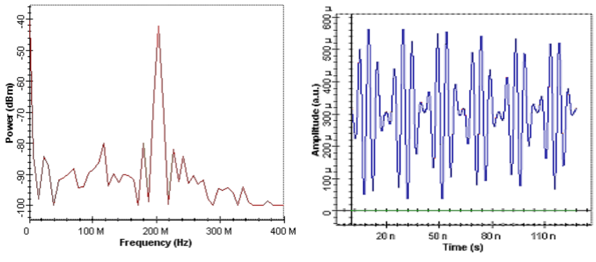


(a) **(b)**

Fig.-10: RF spectrum at RAU (a) OFM generated harmonic at the output of photo detector. (b)

Inter-modulation terms produced by frequency mixer.

It indicates the *fm, fo, fo-fm & fo+fm* intermodulation terms which have the amplitude modulated signal. For the down-conversion of the 5.8 GHz carriers to 200 MHz carrier, *fo-fm* intermodulation term has been selected with the Bessel higher-order low pass filter. Now the down-converted AM signal carrier i.e. 200 MHz is transmitted to the fiber link for Central Station (CS).



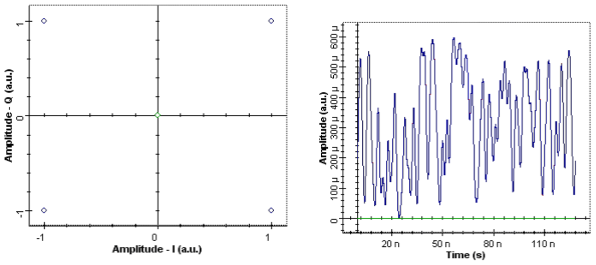
(a) **(b)**

Fig.-11: RF spectrum at CS (a) AM spectrum of 200 MHz carrier at the output of the photo detector at the CS (b) The AM modulated signal recovered at CS

After the transmission of AM signal to the fiber link at the CS, AM signal has been recovered with the receiver. Figure-11(a) shows the AM spectrum of the 200 MHz carriers with 20MHz modulating signal at the output of the photo detector. Figure-11(b) shows the AM modulated signal recovered from the optical carrier at the CS. It is observed that using the OFM generated harmonic carrier as a LO, data comes from the wireless channel may be down-converted easily. The data is recovered from this down-converted carrier at the Central Office successfully.

B. QAM Data Transmission

The methods used to generate the Quadrature Amplitude Modulation (QAM) modulated carrier is similar to the one used in the Amplitude modulation uplink system. The subcarrier frequency of 550 MHz is used in the QAM transmitter. Figure-12 shows the uplink transmission of the QAM data with OFM technique. Figure-12 (a) shows the constellation diagram of the QAM data at the RAU, which receives from the wireless channel. Figure-12(b) shows the QAM modulated data at CS after the photo detector.



(a) **(b)**

Fig.-12: QAM Uplink transmission. (a) Constellation diagram of the QAM (b) QAM modulated data at Photodiode output.

Besides the generation and transportation of simple modulation formats, the complex modulation formats like BPSK, DPSK, QPSK, and QAM are also possible to transmit with OFM. This type of data transmission required a longer simulation time window (enough data points), which could not be achieved due to insufficient computation resources.

IV. CONCLUSION

In this paper, with the simulation set up on OptiSystem, the principal of Optical Frequency Multiplication is demonstrated. The combination of CW laser diode, the frequency modulator, an external MZM modulator with FPI periodic interferometer is successfully used as an optical source for generating the higher-order harmonics at high frequencies. The relative strength and frequency of the harmonics are strongly dependent on sweep frequency, FSR, frequency deviation, FM index and the proper alignment between the laser and the filter. The different data format like ASK, QAM and AM is transmitted in both direction downlink as well as uplink successfully with the up-converted and down-converted carrier respectively. In the downlink, AM modulated signal at 200 MHz at the CS has been recovered from 4^{th}, 6^{th} and 8^{th} harmonics, corresponding frequencies at 11.8 GHz, 17.8 GHz and 23.8 GHz at the base stations with the power level of 10 dbm, -10 dbm and -20 dbm respectively. In a similar way ASK data is recovered from the 4^{th} harmonic of 12 GHz. In the uplink transmission, OFM generated microwave carrier of the frequency of 6 GHz is used as an LO for down-converting the uplink amplitude modulated radio frequency signal of 5.8 GHz to a low IF of 200 MHz, which is returned back to the CS. The QAM data at 550 MHz subcarrier is also recovered at CS successfully from 4^{th} harmonic. Hence, the OFM system is used to perform a large number of functions namely generation of the high-frequency carrier, optical signal transportation, frequency up-conversion, and bi-directional data transmission through generated harmonics simultaneously.

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AUTHORS PROFILE

Rajesh was born on May 4, 1976. He received the M.Tech (Electronics and Communication Engineering) degree from I.K.G. Punjab Technical University, Jalandhar (India) in 2006 and presently pursuing the PhD degree from I.K.G. Punjab Technical University, Jalandhar (India). Presently, he is working as Project Manager in Haryana State Electronics Development Corporation (HARTRON), Panchkula, Haryana (India). He has around 15 years of experience in the installation, operation and maintenance (IO&M) of Optical Fibre Communication Systems in Bharat Sanchar Nigam Limited (BSNL).

His research interests are optical fibre communication and synthesis, characterization and application of polymers, block copolymers, polymer thin films, organic-inorganic composite and nanocomposite materials.