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An Investigation of Millimeter Wave Generation Schemes for Future Networks

Nidhi[1], Ajay Kumar[2], Sandeep Dahiya[3]

[1,3]Bhagat Phool Singh Women University, Khanpur Kalan, Sonepat, India

[2]Guru Jambheswar University of Science and Technology, Hisar, India

nidhimalik008@gmail.com, ajaypunia506@gmail.com, sandeepdahiya@bpswomenuniversity.ac.in

Abstract

Optical generation of MMW is a viable solution for operation at higher frequencies. Integration of RoF transmission with existing cellular transmission offers a low-cost solution for futuristic high-speed communication networks. This study investigates various methods for the optical generation of Millimeter waves (MMW) and the effectiveness of the Radio over Fibre system for their transmission. This brief summary of the key research on photonic generation of MMW will motivate researchers to develop improved techniques for MMW generation and transmission with minimal system cost and complexity.

Keywords: Millimeter wave, External modulation, Wavelength conversion, Optical heterodyne, MZM, OSSR, RFSSR

1 Introduction

Devices connected to the internet consume significant amounts of data, driving demand for greater bandwidth. By 2030, mobile data usage is expected to increase 20,000 times compared to current levels [1]. The current communication technology and networks must be upgraded to meet this data requirement. The key solution involves using higher frequencies where high bandwidth is available. 5G and next-generation communication networks are using the MMW frequency spectrum due to its wide bandwidth and potential to deliver high-data-rate services to consumers [2]. However, the electronic generation of high-frequency signals beyond 30 GHz is limited by various factors. Over the past few years, optical generation of high frequencies has attracted significant attention. The smart RoF method uses both optical and wireless systems to increase the access network's capacity at minimal cost. However, RoF technology offers a simple, cost-effective architecture with centralised signalling, minimising operational costs and reducing latency.

2 RoF System

The RoF system can be divided into three major subsystems: a central station (CS) or base station as a transmitter, an optical fibre network, and a remote access unit (RAU) as a receiver, as shown in Fig. 1. Modulation techniques and signal generation are controlled at the central station (CS). In CS, the electrical signal is converted into an optical signal, which is then utilised to interact with remote access units (RAUs) via OFN. Optical fibre network (OFN) uses its remote nodes where the optical signal gets boosted and distributed to RAUs by using the demultiplexing technique. The RAU includes an antenna that receives an optical signal and change it back to the electrical signal before sending it to the user.

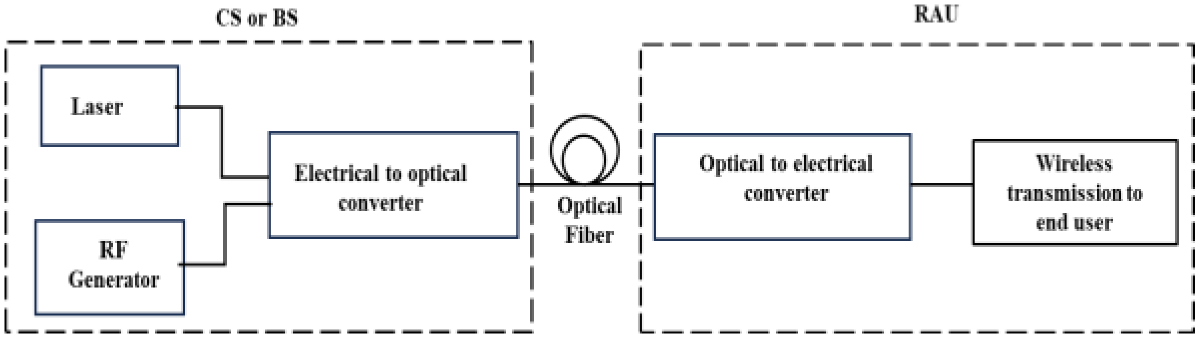

Fig. 1. Block diagram of RoF System [3]

3 Frequency Millimeter Waves Generation Techniques: Fig. 2 shows the techniques of MMW generation including external modulation, wavelength conversion and optical heterodyne. Photonic generation of mm waves is a viable solution where optical nonlinear devices such as optical modulators namely Electro-absorption modulator (EAM), Phase modulator (PM), and Mach Zehender modulator (MZM), Semiconductor optical amplifier (SOA) and optical fibers are utilised [4].

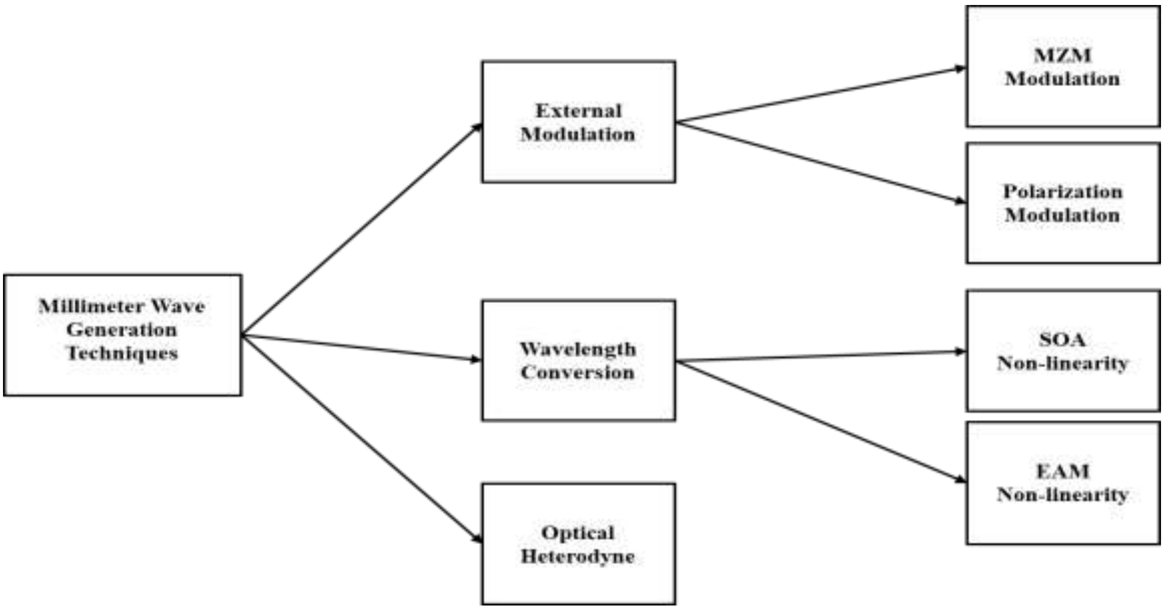

Fig.2. Millimeter Wave Generation Techniques

3.1. External modulation

External modulation technique involves modulation of optical signals with the help of an external modulator which could be either an intensity modulator MZM or PM or EAM. Light signal is modulated by using low frequency RF signal. The generated optical signal comprising higher frequency sidebands is propagated via optical fiber [5]. MMW high-frequency signal is produced when desired sidebands are allowed to beat at the photodetector.

a) MZM modulation

The block diagram of external modulation based on Mach Zehender Modulator (MZM) is presented in Fig. 4. MZM has become a significant research area, providing higher spectral purity, a high frequency multiplication factor, a wide bandwidth and excellent frequency tunability [6]. The Mach Zehnder Modulator has been mostly used in external modulation and offers chirp-free operation with the modulation bandwidth of approximately 60 GHz. There are two varieties of MZM depending on the number of driver ports namely single-drive MZM and dual-drive MZM (DD MZM) [7].

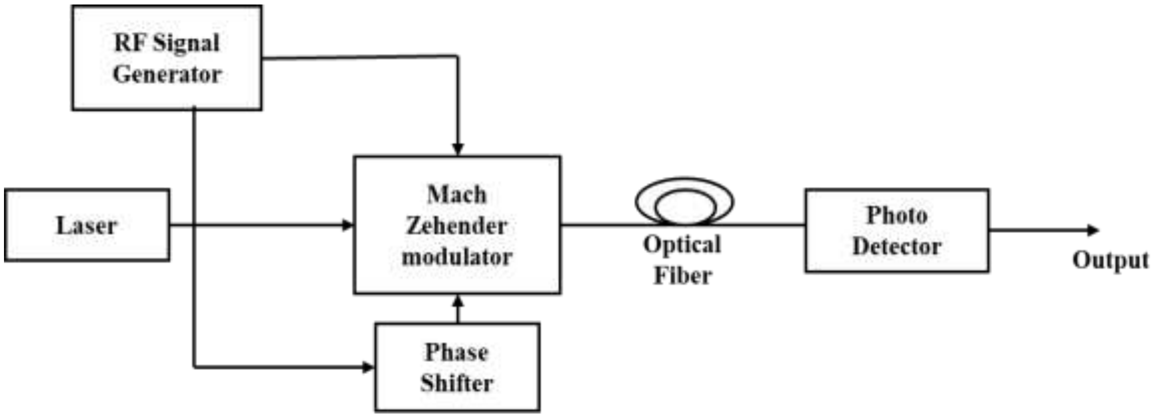

Fig. 4. Block diagram of MZM based External Modulation [8]

Low frequency drive signal is modulated by optical carrier signal using MZM biased at minimum or maximum transmission point (MATP or MITP). The MZM output is a modulated optical signal comprising of dominating higher desired sidebands and weak undesired sidebands. This signal is propagated via optical fiber to a photodetector where higher desired sidebands beat to produce mm wave signal.

b) Polarization Modulation

PoLM basically transforms transversal electric modes into transversal magnetic ones. Fig. 5 is a block diagram of the polarization modulation link. The semiconductor laser output optical signal is modulated by an RF signal using PoLM. The resulting signal is then transmitted through a non-polarization maintaining optical fiber and polarization controller [9]. When linearly polarized light enters in half wave plate (HWP) or polarization rotator, its polarization path is rotated. The amount of rotation is defined by the plate's orientation with respect to the polarization of the incoming light. The phase difference between the two components of polarized light is reduced by half a cycle using half-wave plate resulting in an 180^0 phase shift. A polarization beam splitter performs intensity modulation on the polarization modulated signal and allows to be photo-detected [10].

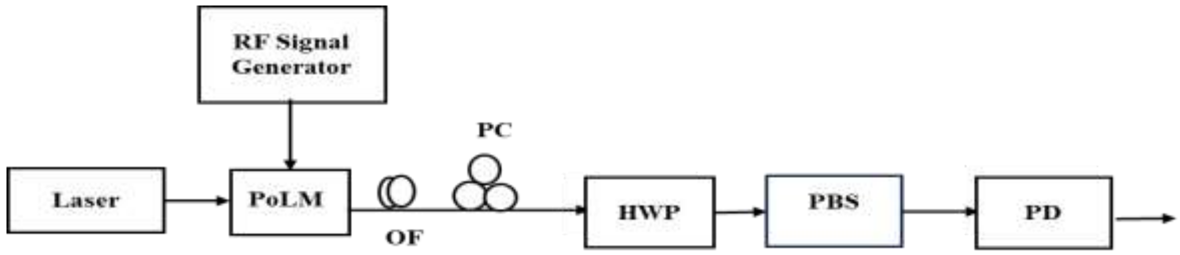

Fig. 5. Block diagram of Polarization Modulation [11]

[PolM: Polarization modulator, OF: Optical Fiber, PC: Polarization controller, HWP: Half wave plate, PBS: Polarization beam splitter, PD: Photo detector,]

A number of significant research works employing external modulation based on Mach-Zehnder Modulators (MZMs) and PolM have been reviewed and summarized in Table 1. These studies successfully achieved frequency multiplication factors (FMFs) of 4, 6, 8, 10, 12, 16, 18, 24, 32, 36, 40 and 48. The desired FMFs were realized through appropriate selection of system parameters and specific configurations of cascaded or parallel MZM, DP-MZM, DD-MZM and PolM.

Table 1 A Framework of Review Literature of External Modulation

Optical K-Tupling	Author with references	Technique	Findings
Quadruple	Nael, *et al.* in 2013 [12]	Based on two parallel Mach Zehnder modulators at 25 dB extinction ratio (ER) and without the need of filter.	60 GHz MMW obtained with 40 dB OSSR and 35 dB RFSSR with carrier suppressed.
Sixtuple	Zihang, *et al.* in 2017 [13]	Based on dual parallel MZM and without using filter.	36 GHz MMW, 38.5 dB OSSR and 32.8 dB RFSSR, no requirement to carefully adjust modulation index.
Octuple	Ahmed, *et al.* in 2020 [14]	Employed 4 MZM, two polarizers and no used of filter.	80 GHz MMW, 68.4 dB OSSR and 62 dB RFSSR, wide range of modulation index.
Tentuple	Muthu, *et al.* in 2017 [15]	Used of DP-MZM.	60 GHz MMW achieved, observed 0.4 dB power penalty achieved 75 km transmission.
12-tuple	Ankita, *et al.* in 2024 [16]	Employed three Cascaded MZM and polarization multiplexing assisted carrier suppression.	60 GHz MMW received with 62.06 dB OSSR and 54.79 dB RFSSR, broad modulation index range extending from 1.5 to 4.5 and good frequency tunability, robustness against parameter deviations.

16-tuple	Zufang, *et al.* in 2024 [17]	Based on four cascaded PolM and without need of filter.	160 GHz MMW achieved, biasing not required, low modulation index, 64.21 dB OSSR and 60.99 dB RFSSR.
18-tuple	Xueyao, *et al.* in 2024 [18]	Utilized three parallel polarization modulators, two phase modulator and electrical phase shifter and filterless technique.	Achieved 180 GHz MMW, 48.02 dB OSSR and 42.55dB RFSSR, biasing is not required.
24-tuple	Ankita, *et al.* in 2023 [19]	Based on three cascaded MZM, polarization multiplexing and filterless technique.	4.5 dB power penalty at 26 km transmission distance, achieved 120 GHz MMW, 51.23 dB OSSR and 44.82 dB RFSSR.
32-tuple	Xinqiao, *et al.* in 2023 [20]	Utilizing two cascaded DP-MZM with maximum transmission point and without need of filter.	Generated 160 GHz MMW, use of polarization multiplexing to suppress carrier, 53.53 dB OSSR and 47.33 dB RFSSR, DC bias drift.
36-tuple	Krishna, *et al.* in 2025 [21]	Employed two cascaded DP-MZM.	180 GHz MMW, 20 Gbps bit rate across 50 km single mode fiber used, OSSR is 52 dB, RFSSR is 46 dB.
40-tuple	Xinqiao, *et al.* in 2023 [22]	Employed three MZM with optical filter, remodulation and fiber bragg grating used.	200 GHz MMW, transmission distance 90 km, 80.71 dB OSSR and 70.3 dB RFSSR.
48-tuple	Ajay, *et al.* in 2024 [23]	Use of two DP-MZM and remodulation employed.	120 GHz MMW, improved sideband suppression ratio using optical demultiplexer, OSSR of 48 dB, RFSSR of 34 dB.

3.2. Wavelength conversion

Wavelength conversion is a method of converting the wavelength of an optical signal to a different wavelength. These techniques use semiconductor optical amplifier (SOA) nonlinearity or electro absorption modulator (EAM) nonlinearity to generate mm waves.

a) SOA non-linearity

Semiconductor optical amplifier is frequently used for RF frequency conversion due to their small size and ability to be integrated with other optical devices. The four types of non-linerarities in SOA namely cross-gain modulation (XGM), cross-phase modulation (XPM), four-wave mixing (FWM) and cross-polarization modulation (XPolM) can be implemented to perform frequency mixing. The mm waves can be generated using SOA non linearity in RoF system as depicted in Fig.6. The optically modulated signal is applied to SOA. The FWM effect in SOA results into generation of multiple higher frequencies. The desired frequencies are filtered and transmitted via optical fiber [24].

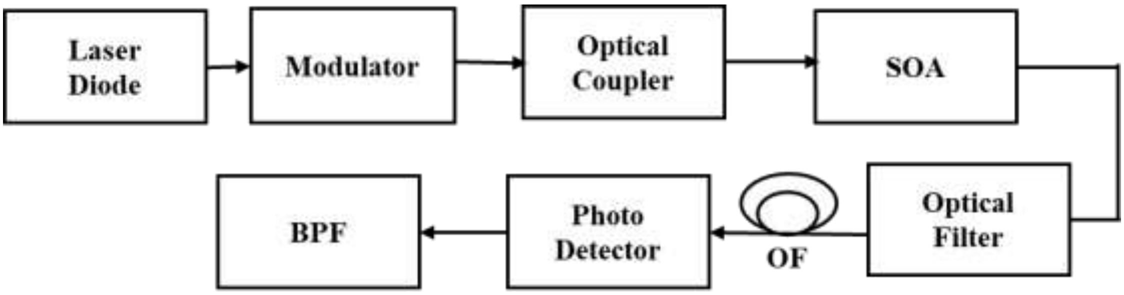

Fig. 6. Block diagram of RoF system using SOA non-linearity [25]
[BPF: Band pass filter]

The table no 2 reflects significant research work done on wavelength conversion based on SOA non-linearity.

Table 2 Previous work on wavelength conversion based on SOA non-linearity

Tupling	Author with references	Technique	Findings
18-tuple SOA	Zhou, *et al.* in 2021 [26]	Based on MZM-SOA combination with 1.5 dB power penalty and use of interleaver.	Generated 90 GHz MMW, 20 km single mode fiber transmission, W-band, Sideband ratio (SR) is 3.41 dB and injection current is 0.37 A.
24-tuple	Zhou, *et al.* in 2018 [27]	Employed DP-MZM SOA with tunable optical filter and use of interleaver.	Generation of $8f_{RF}$, $16f_{RF}$ and $24f_{RF}$ for different base stations, 60 GHz MMW, 40 km optical fiber transmission, SOA injection current is 0.32 A.
30-tuple SOA	Ajay, *et al.* in 2024 [28]	Based on DP-MZM SOA.	150 GHz MMW, data transmission 20 km, generation of frequencies 50 GHz, 100 GHz and 150 GHz, SR of 3.63 dB with SOA injection current of 0.6 A.
36-tuple SOA	Kunkun, *et al.* in 2022 [29]	Based on DP-MZM SOA and use of interleaver.	180 GHz MMW, 20 km fiber transmission, SR of 0.4 dB at SOA injection current is 0.12 A.

SOA injection current plays a significant role in controlling the non-linear gain and the resulting sideband ratio (SR). Future work may explore bias-free SOA operation, integrated photonic platforms and phase-stable multi-frequency systems to enhance spectral efficiency and deployment feasibility.

b) EAM non-linearity

Electro-absorption modulator (EAM) applies nonlinear cross absorption modulation to achieve frequency mixing with wide wavelength bandwidth. Cross Absorption Modulation (XAM) is a nonlinear optical phenomenon where one optical signal controls the absorption of another optical signal within EAM. EAMs have involved a lot of attention due to its many merits, like simple structure, small size, low chirp [30]. The demerits include requirement of high pumping power and low conversion efficiency [31]. Fig. 7 shows a block diagram of RoF system based on EAM nonlinearity. The output of EAM is directed into the fiber. The traveling signal is received by the photodiode and the signal is monitored using the probes. The research work on EAM based wavelength conversion techniques is reviewed and presented in table 3.

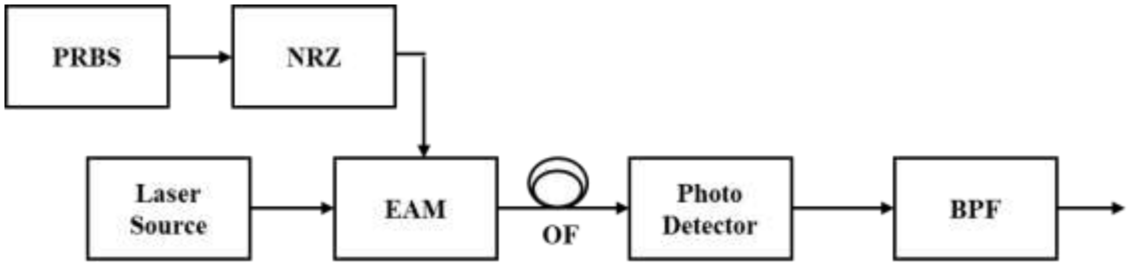

Fig. 7. Block diagram of RoF system using EAM non-linearity [32]

[PRBS: Pseudo random bit stream, NRZ: Non return to zero]

Table 3 Relevant work on EAM based wavelength conversion

Author with references	Technique	Findings
Chul, *et al.* in 2005 [33]	Based on EAM-XAM and use of optical circulator and isolator.	26 GHz, wide wavelength bandwidth, spurious free dynamic range (SFDR) is 85.9 dB.Hz$^{2/3}$, Phase noise is -76.8 dBc/Hz.
Palaci, *et al.* in 2010 [34]	Used EAM-SOA, variable optical attenuator and optical bandpass filter employed.	64-QAM signal, error free performance upto 40 GHz achieved, SFDR of 52.5 dB.Hz$^{2/3}$.
Hyoung, *et al.* in 2011 [35]	Employed EAM and variable optical attenuator.	Phase noise is -92dBc/Hz, do not require a dc bias controller.
Taranjeet, *et al.* in 2017 [36]	EAM	Use of different wavelengths, good conversion efficiency, extinction ratio is improved by increasing probe signal power.

3.3. Optical heterodyne

Figure 8 shows the diagram of RoF system based on optical heterodyne technique. In this technique two incoherent single longitudinal mode lasers produce optical carriers with different frequencies. These carriers are coupled in a coupler and transmitted via an optical fiber. Once the signals reach the photodetector (PD), the resulting beat frequency generates an optical

MMW signal characterized by the frequency difference between the light waves emitted by the two incoherent single longitudinal mode lasers [37].

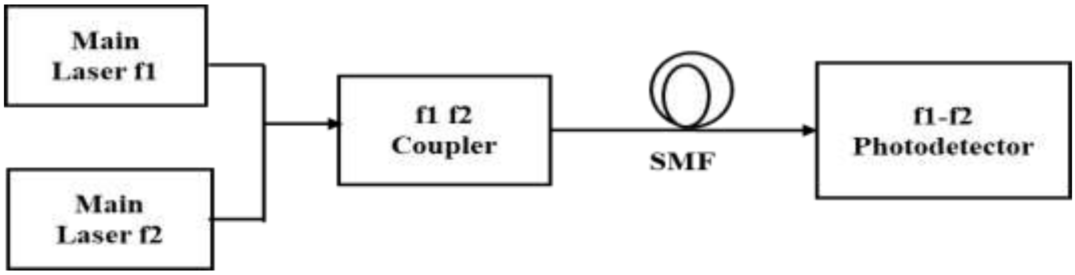

Fig. 8. Block diagram of RoF system based on optical heterodyne techniques

The phase of optical signals output by two independent lasers results in undesirable system noise. A stable MMW signal with minimum phase noise is only generated when the laser's performance satisfies specific requirements, ensuring alignment in phase, amplitude and polarization states. The advantages of optical heterodyne technique is that the generated MMW has high signal frequency, high SNR and high gain. The details significant research work done on optical heterodyne presented in Table 4.

Table 4 Literature review of optical heterodyne

Author with references	Technique	Findings
L.N.Langley, *et al.* in 1999 [38]	Employed optical phase locked loop (OPLL)	Phase noise reduction not required, wide bandwidth feedback, Phase error variance is 0.05 rad^2, acquisition range is 370 MHz.
Jing, *et al.* in 2009 [39]	Based on two step heterodyne with optical carrier suppression modulation and fiber bragg grating (FBG).	72 GHz and 60 GHz MMW, no MMW power degradation due to chromatic dispersion, increase in laser's linewidth degrades the BER performance.
Arash, *et al.* in 2011 [40]	Employed quadrature phase shift key (QPSK) and binary phase shift key (BPSK).	Investigation of BPSK and QPSK at 60 GHz and heterodyne method at 12 GHz, plot of BER vs SNR for different transmission distances, Transmission distance 20 km, BER is 10^{-5} at 20 km transmission distance.
Abhijit, *et al.* in 2017 [41]	Optical injection phase locked loop (OIPLL) and phase margin.	OIPLL is more stable than conventional OPLL in presence of loop delay, Phase margin
Kongfan, *et al.* in 2019 [42]	Based on optical carrier suppression (OCS) and optical injection locking (OIL).	60 GHz MMW, phase noise eliminated, high Q factor, more suppression of central wavelength, error free transmission up to 40 km.

Drissa, *et al.* in 2020 [43]	Optical heterodyne generation and Self-homodyne detection.	100 GHz MMW generation, implementation of two different heterodyne schemes with ODSB (optical double sideband) and OSSB (optical single sideband) modulation, EVM results show OSSB can achieve better transmission performance over ODSB, W- band operation.

5 Conclusion

The paper presented a detailed investigation of various MMW generation techniques such as external modulation, wavelength conversion and optical heterodyne. The performance of these techniques is measured by the authors using several parameters including OSSR, RFSSR, Fiber transmission length, BER, Q-factor etc. It has been observed that a lot of research work has been carried out using external modulation while wavelength conversion and optical heterodyne techniques are yet to be an exploring pathway of the research. This study will contribute to the progress of improved optical MMW technology for next generation networks.

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