Simulation and Analysis of Radio over Fiber (RoF) Systems using Frequency Up-Conversion Technique

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ABSTRACT
Radio-over-Fiber (RoF) technology is an integration of microwave and optical networks [1]. RoF technology uses optical fiber as a backend technology due to the enormous advantages offered by it. SCM-WDM RoF systems (Sub-carrier based Wavelength division multiplexing RoF system) improves spectral efficiency with high dispersion tolerance [7]. The data to be transmitted is electrically modulated with an IF (Intermediate frequency)or a RF (Radio frequency) carrier and electrically multiplexed using a multiplexer these signals are further optically modulated using an optical modulator and multiplexed using WDM to exploit the high bandwidth offered by the optical fiber. A comparison between IF over fiber and RF over has been analyzed in terms of quality factor and BER (Bit error rate) in a RoF system. In which the IF over fiber shows better performance than RF over fiber in terms of BER and Quality factor. IF signals are up-converted using HBT (Hetero-junction bipolar transistor) electronic mixer in the remote antenna units to the RF frequencies with the help of LO (local oscillator) and transmitted wirelessly [27].

General Terms
Wireless communication systems, Optical fiber communication, Subcarrier multiplexing, Wavelength division multiplexing, Radio-over fiber systems.

Keywords
External optical Modulation, Frequency up-conversion, remote antenna units, IF based RoF system, RF based RoF system, HBT (Hetero-junction bipolar transistor).

1. INTRODUCTION
In today's era of ubiquitous connectivity or "communication anytime, anywhere and with anything". The demand to have broadband capacity wirelessly has put pressure on wireless communication systems to increase both their transmission capacity, as well as their coverage [1]. Research on millimeter waves has gained attention recently. High frequencies in the range of GHz have more bandwidth, hence their data carrying capacity are more, but they encounter more losses when they are transmitted wirelessly hence they cannot be transmitted long distances whereas the low frequency signals encounters less losses hence they can travel long distances. At high frequency associated losses are high. Hence, there is a need for a waveguide to carry these waves. The medium is nothing but optical fiber due to the low loss offered by them (0.2 dB/km) in 1550nm band which is much smaller than any other medium can provide. In order to meet the ever increasing demand for larger transmission bandwidth. Wireless network based on radio over-fiber technologies is a very beneficial solution. It acts as a back-end technology for the transportation of microwave and millimeter waves [1].

RoF is a well-established technique for the distribution of wireless communication systems due to the larger bandwidth offered by optical fiber and the add drop facility offered by the WDM systems makes it suitable to add and drop any channels simultaneously during transmission through Optical add-drop multiplexers (OADMs) [8].RoF makes it possible to centralize the RF signal processing functions in one shared location (Central office), and then to use optical fiber to distribute the RF signals to the remote base stations (BS) from there they are transmitted wirelessly through the remote antenna units (RAUs), as shown in figure 1. By doing so, RAUs are simplified significantly, as they only need to perform optoelectronic conversion and amplification functions. The need for increased capacity per unit area leads to higher frequencies per unit area leads to higher operating frequencies, smaller radio cells and large no of BS. Therefore, cost-effective BS development is a key success to the market [18].

1.1 Architecture of RoF system
RoF systems are classified into three main categories:

1. RFoF (Radio Frequency over Fiber)
2. IFoF (Intermediate Frequency over Fiber)
3. BBoF (Baseband signal over Fiber)

1.1.1 Radio Frequency over Fiber
In RF-over-Fiber architecture, an RF signal (analog waveform) with high frequency (greater than 10 GHz with baseband data embedded in it) can be modulated with light waves.

1.1.2 Intermediate Frequency over Fiber
In IFoF architecture, a data carrying RF signal with frequency (less than 10 GHz) are modulated with light wave using either direct or external modulation before transmission over the optical link. Therefore, before radiation through the air at the remote base station this signal from IF frequency needs to be up-converted to RF level before transmitting them wirelessly through RAUs. IFoF scheme has exhibited a 2dB better sensitivity than RFoF scheme [1].

1.1.3 Baseband signal over Fiber
In BBoF scheme a baseband signal is modulated with light wave and transmitted over optical fiber. Then, at the receiver end this baseband signal is detected and up-converted to RF level by up-conversion techniques. BBoF scheme exhibits better sensitivity than an IFoF scheme by 4dB [1].

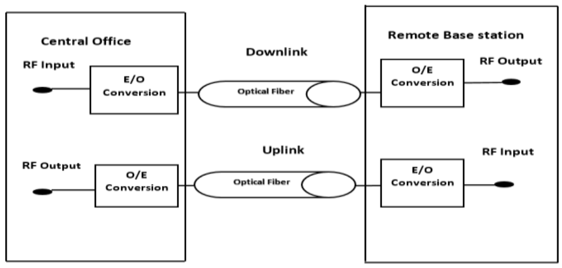

Figure 1.1: Radio-over Fiber Architecture [3]

1.2 Advantages of RoF

Some of the advantages and benefits of the RoF technology compared with electronic signal distribution are given below : (i) Low Attenuation loss: optical fiber offers very low loss hence RoF technology can be used as a backbone for transporting microwave or millimeter waves from central station to base stations (ii) Large Bandwidth: Optical fibers offer enormous bandwidth however, todays state-of-the art commercial systems utilize only a fraction of this capacity (iii) Low RF power remote antenna units (RAUs) has many benefits such as Increased battery life of mobile terminals, Low generated interference, Easier frequency/network planning and relaxed human health issues (iv) Dynamic resource allocation: For instance in a RoF distribution system for GSM traffic, more capacity can be allocated to an area during busy hours and then re-allocated to others areas. (v) Centralized upgrading: As most of the signal processing operations take place in central station the remote base station is simpler. (vi) Line of sight (LOS) operation (multipath fading effects are minimized) as the signals are carried out by optical fiber the losses that occur during wireless transmission systems are avoided to a greater extend. (vii) Immunity to Radio Frequency Interference: is a very attractive property of the optical fiber, which also provides privacy and security [1-4].

2. MULTIPLEXING TECHNIQUES

Multiplexing techniques play an important role in achieving high spectral efficiency hence, to select an appropriate multiplexing technique with high spectral efficiency, enhanced performance and lower complex is a necessity for RoF systems. RF multiplexing techniques such as Sub-carrier multiplexing (SCM) is used and due to optical backend multiplexing techniques such as Time division multiplexing (TDM), orthogonal frequency multiplexing (OFDM) and Wavelength division multiplexing (WDM) are also used. The combination of two multiplexing techniques such as SCM and WDM has recently gained importance due to its high spectral efficiency and reduced complexity [7].

2.1 A combination of both SCM based WDM RoF systems

In order to take advantage of both the multiplexing techniques a combination of SCM based WDM systems are used. SCM systems are more mature hence, RF modulation, filtering can be done in the electrical domain whereas WDM systems provides enormous bandwidth. As shown in figure 2.1 SCM is used as electrical side multiplexing whereas WDM is used as an optical side multiplexing. On the receiver side the optical WDM systems are de-multiplexed and detected by a photo-detector to respective wavelengths which are further de-multiplexed into respective RF as shown in figure 2.2. The combination of SCM based WDM systems may provide a flexible platform for high-speed optical transport networks with high optical bandwidth efficiency and high dispersion tolerance [18, 20].

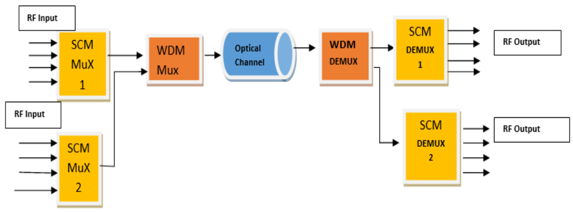

Figure 2.1: A combination of SCM-WDM RoF systems [18]

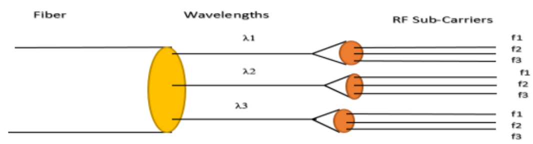

Figure 2.2: De-multiplexing of WDM and SCM in the receiver side of RoF systems [16].

2.2 Frequency up and down conversion

Frequency up and down conversion is a technique where instead of RF signal IF signal is transmitted over optical fiber. The transmitted IF signal is free from the fiber dispersion effect. There are many reported frequency conversion techniques using an external modulator, optical heterodyne, optical transceiver, using nonlinear effects such as Four-wave mixing (FWM) [12], Stimulated Brillouin scattering [11], using mixers such as Heterojunction bi-polar transistor (HBT) [21], High electron mobility transistor (HEMT), Avalanche photodiodes etc.

2.2.1 Frequency conversion using Mixers

Electronic mixers such as Si-Ge based HBTs are used on the receiver side where the frequency is up-converted before transmitting wirelessly to the end users. The optical signal is first demodulated using photo-detector in the receiver end and then it is up-converted to the required radio frequency level. Any device used as a mixer must have strong non-linearity, low noise, low distortion and adequate frequency response. An electrical mixer consists of two input port and one output port as shown in figure 6. In which one input is given as IF input signal and the other input port is given a pump waveform which is known as local oscillator (LO) port is required to pump the mixer. LO signal is the strongest and hence it is used to transform IF signal to RF during downlink and RF to IF signal during uplink [25].

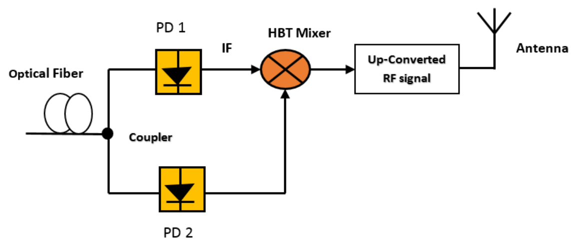

Figure 2.3: Frequency up-conversion at receiver side using an HBT mixer [25].

3. SYSTEM DESIGN

Our proposed RoF system is simulated using Optisystem software 7.0.Central System (CS) which consists of four pseudo random sequence bit generator generating binary signals which are converted into electrical by using Phase-shift keying modulator (PSK) in this way four electrical carrier signals are generated from, which two signals are electrically multiplexed using a Combiner 1 as shown in figure 3.1 which are further converted into an optical signal by externally modulating it with a continuous wave (CW1) laser and a Mach-Zehnder Modulator (MZM1) the central wavelength of CW1 laser is 1551 nm.

The other two signals are further electrically multiplexed using Combiner 2 which is further converted into an optical signal by external modulation using CW2 and MZM2 with a central wavelength of 1552nm. These two optical signals are of wavelengths 1551nm and 1552nm which are further multiplexed using Wavelength division multiplexer (WDM). In our proposed system, we have used wavelength which falls under C-Band where attenuation is minimum and hence it achieves the longest range. The wavelength multiplexed signal is carried over a single mode fiber (SMF) for a distance of 50 km with a data rate fixed at 2 Gbps, then it is amplified using an optical amplifier with gain 20dB and noise figure 4dB [20].

3.1 IF based RoF system

Instead of modulating the RF signal with an optical signal we are using IF signal. IF (frequency less than 30 GHz) is modulated with optical signal. Four IF carrier signals which are applied in our system design are 5 GHz, 10 GHz, 15 GHz and 25 GHz As, shown in fig 3.1, 5 GHz and 10 GHz PSK modulated signals are multiplexed using combiner1 then, 15 GHz and 25 GHz signals using combiner 2. Then, these two signals are optically modulated using MZM and converted into wavelength 1551nm and 1552 nm using CW1 and CW2 and further multiplexed into optical domain using WDM and passed through the fiber.

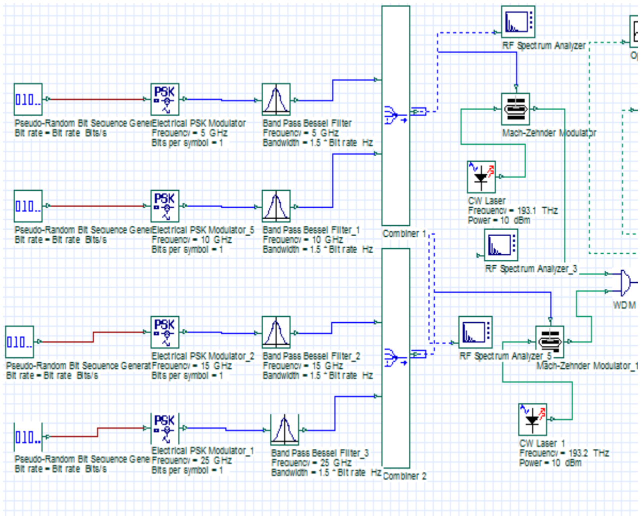

Figure 3.1: IFoF over fiber system.

BER, Q factor and Power value of the IF signals obtained at the receiver end are tabulated in table 1.

Table 1: Intermediate frequency BER, Q factor and power

Frequency (in GHz)	BER	Q factor (in dB)	Power (in dBm)
5	4.57E-58	16.0289	-26
10	6.34E-14	7.40947	-28
15	8.88E-18	8.50718	-44
25	3.70E-111	22.3718	-54

3.2 RF based RoF system

In, our system instead of IF we are now modulating RF with an optical signal. Four RF signals used in our design are 15 GHz, 30 GHz, 45 GHz and 75 GHz. The system design is same as IFoF only instead of IF, RF signals are used as shown in figure 3.2. BER, Q-factor and power values of RF signals obtained at the receiver are tabulated in below table 2.

Table 2: Radio frequency BER, Q factor and power

Frequency (in GHz)	BER	Q factor	Power (in dBm)
15	1.25E-22	9.71721	-44
30	4.27E-06	4.45093	-52
45	0.0302402	1.87724	-60
75	1	0	-72

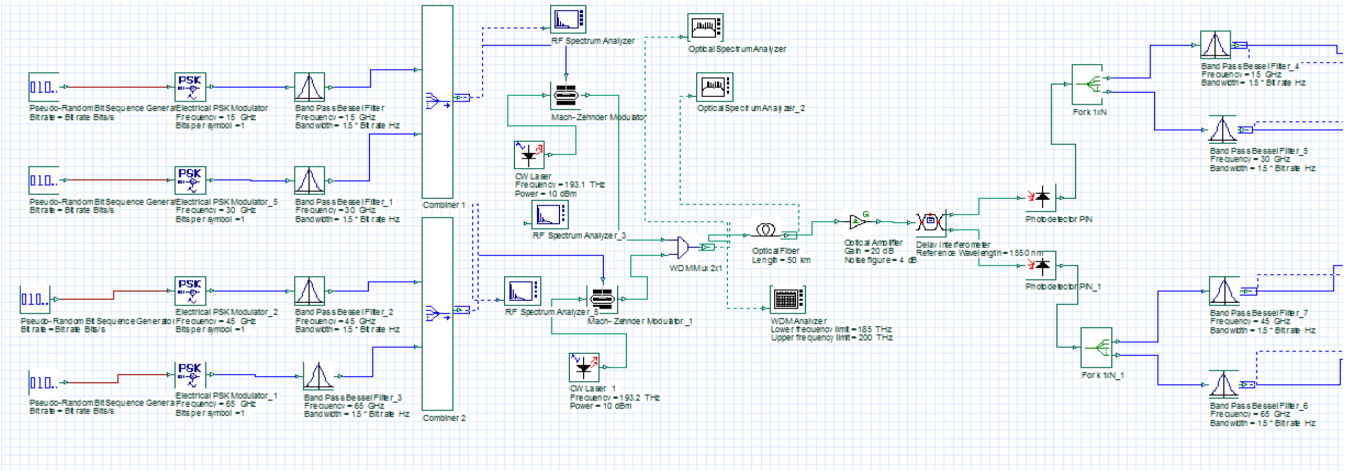

Figure 3.2: RFoF over fiber system.

3.3 Comparison of IF and RF based RoF system.

Comparison of IF over fiber and RF over fiber are done using the BER, Q-factor and power values obtained from the respective frequencies by keeping the data rate and fiber length constant at 2 Gbps and 50 km.

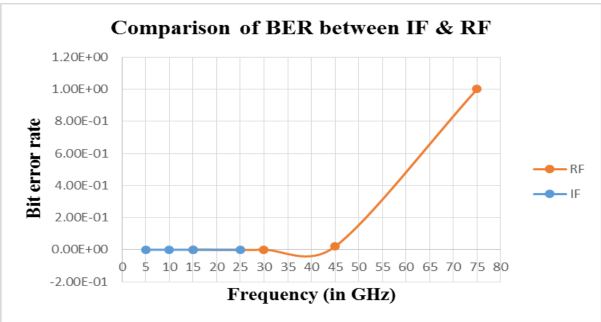

Figure 3.3: BER versus frequency.

From, the table 1 and 2 BER versus frequency graph has been plotted which shows that the BER for high frequencies (i.e. RF 15 GHz, 30 GHz, 45 GHz and 75 GHz) are more whereas, BER for low frequencies such as IF (5 GHz, 10 GHz, 15 GHz and 25 GHz) is less. The BER value for RF increases steadily as the frequency increases. Whereas, the BER for IF is constant and lesser than RF.

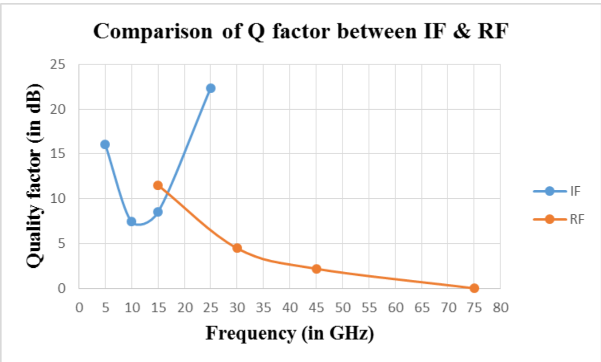

Figure 3.4: Q-factor versus frequency

From, the graph shown in figure 3.4 we can conclude that Q-factor value for IF signal from 5 GHz decreases till 10 GHz after that it increases gradually for 15 GHz and 25 GHz. Whereas, in case of RF signal the Q-factor decreases steadily from 15 GHz till 75 GHz. IF frequencies have acceptable Q-factor level whereas, for RF signals Q-factor value decreases sharply. Q-factor value for 45 GHz and 75 GHz is too low and below expected level.

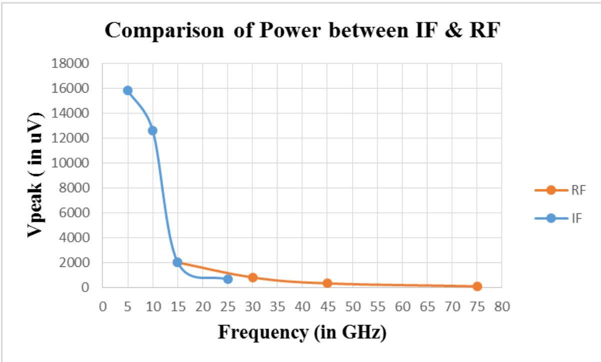

Figure 3.5: Power versus frequency.

The power value for IF and RF is expressed in terms of ultra-volts. Power for IF signal is better than RF. Dynamic range is very important in wireless systems hence, power is an important factor describing signals.

From the above three graphs in figure 3.3, 3.4 and 3.5 we can conclude that IF over fiber is more beneficial than sending RF over fiber. But, the practical difficulty in sending these IF over fiber signals is that they need up-conversion in the receiver end (i.e. A remote base stations) before, being transmitted wirelessly. These Up-conversion while downlink and Down-conversion while uplink makes the receiver end more complex. Hence, there was a need for up-conversion technique. We have used HBT (Hetero-junction bipolar transistor) mixer in our system due, to its less complexity, cost effectiveness and high conversion gain and its usage can be extended up-to millimeter wave signals range.

4. FREQUENCY UP-CONVERSION USING HBT MIXER

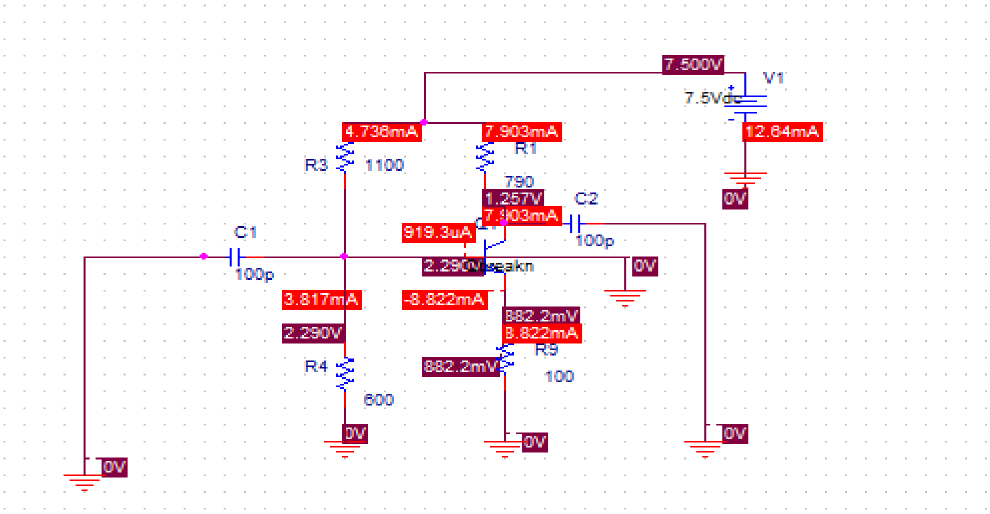

Figure 4.1: DC bias of HBT mixer circuit.

The design steps are divided into 5 parts. These are the DC biasing of the mixer circuit, S-parameters measurement of RF and IF, input matching, output matching and final design verification.

In this work, Agilent Hetero-junction transistor has been used the PSPICE parameters used for modelling the transistor has been tabulated below in table3. The DC biasing point obtained after simulation is as shown in figure 4.1 was employed with 7.5 VDC bias voltage. From the simulation, VCE = 1.25 V and IC = 7.9 mA operating point were obtained.

Scattering parameter, or normally known as S-parameter, is one of the crucial requirements in designing any circuit involving with active element such as a transistor. It is essential to determine the S-Parameter so that the maximum power transferred to the circuit, or also known as, circuit matching can be done appropriately.

In our work, we are only interested with the S- and Z-parameters of the desired frequency table 3 below shows the summarized S- and Z-parameters of the main RF mixer designed using HBT. Z-parameters were obtained from the S-parameters to perform the matching transformation. From Z-parameter the impedance matching is obtained at desired frequencies and the input, output ports were designed in order to obtain maximum power transfer.

Table 3: S- parameters and Z-parameters for the desired frequencies.

Frequency in GHz	S11	S22	Z11	Z22
5 GHz	0.453+0.255j	0.599-0.0492j	100+70j	70+45j
10 GHz	0.591+0.198j	0.559-0.0492j	148+96j	174-25j
15 GHz	0.633-0.110j	0.566-0.318j	200-75j	100-110j
20 GHz	0.567-0.0475j	0.551-0.319	178-25j	98-105j
25 GHz	0.503-0.0373j	0.539-0.325j	150-15j	95-102j
30 GHz	-0.299+0.167j	-0.0583+0.195j	25.7+9.75j	41.4+16.8j
45 GHz	-0.0223+0.170j	0.273+0.0986j	45.2+15.8j	85+18.3j
50 GHz	0.204+0.242j	0.302+0.106j	65.0+35.58j	90.3+21.2j
75 GHz	0.627-0.150j	0.332+0.120j	181-93.1j	95.5+26.6j

4.1 Up-conversion of 15 GHz signal using IF 5 GHz and LO signal 10 GHz:

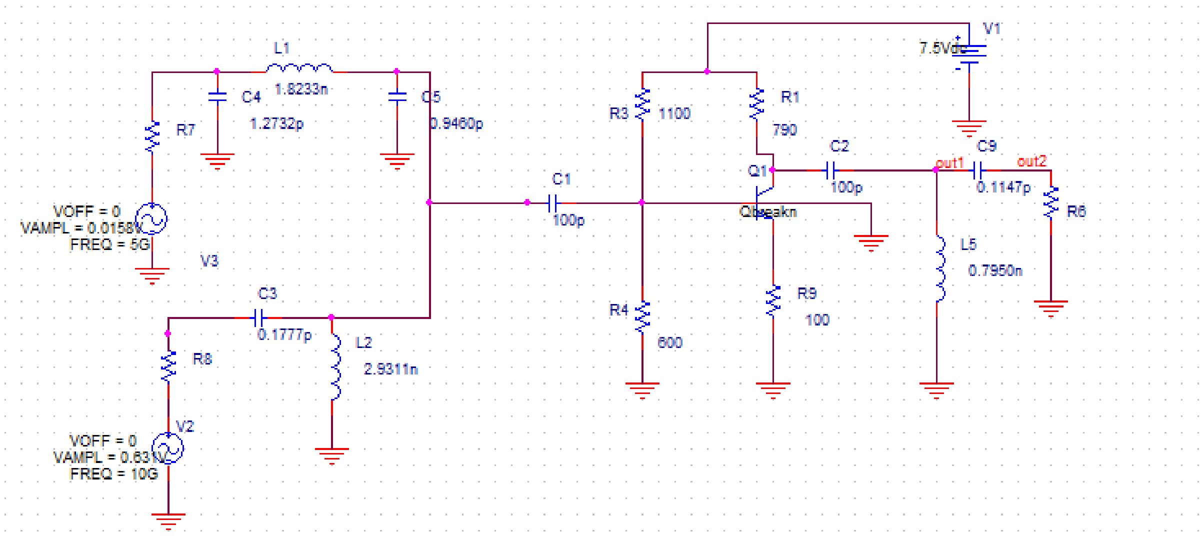

Figure 4.2: Schematic diagram of the Up-conversion mixer circuit for RF 15 GHz [25]

The Schematic diagram of the mixer circuit is depicted in Fig. 4.2. It consists of three ports which are IF and LO ports as the input ports and RF port as the output port. LO power must be higher than IF power since it acts as a driver or pumping signal to control the switching of the mixer. In designing both the input ports, the desired frequencies with their S-parameters should be considered. In order to perform the matching network of IF port, we would like to match the IF input impedance, Z11 for an IF frequency of 5 GHz found in Table 3 with a 50 Ω matching impedance. Similarly for the LO port, we would like to match the LO input impedance, Z11for the LO frequency of 10 GHz that is also found in Table 3 with a 50 Ω matching impedance. We will consider the load or the output impedance instead of the input impedance of the RF port. Therefore, we transformed a 50 Ω to match to the RF load impedance, Z22 for RF frequency of 15 GHz as obtained in Table 3. In carrying out the impedance matching procedure, we are assuming the transistor to be operating in a quasi-linear mode. It is nonlinear, so as to produce the mixing effect, yet the linearity is small enough so that the usual linear procedure and the concept of impedance can be applied. The above system setup is simulated using PSPICE software in time domain.

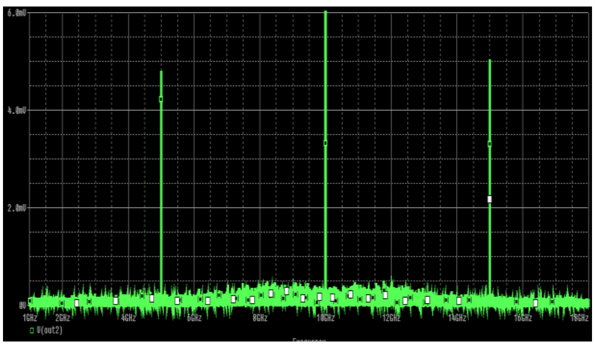

Figure 4.3: Simulated RF output spectrum at 15 GHz.

The output probe window of the PSPICE transient analysis with frequency in its x-axis and Vpeak voltage in its y axis, which is selected to be V (out2) which displays the voltage from the node OUT2 has been shown in figure 4.3. The above figure shows the Vpeak value of the frequencies 5 GHz IF, 10 GHz LO frequency both are the input frequencies and 15 GHz which is the up-converted RF output frequency.

4.2 Up-conversion of RF at 30 GHz

The output spectrum of the HBT mixer using IF at 10 GHz and LO at 20 GHz. The input, LO and output port of the mixer are matched using the impedance values tabulated in table 3. The RF output spectrum obtained in the output probe is shown in figure 4.4.

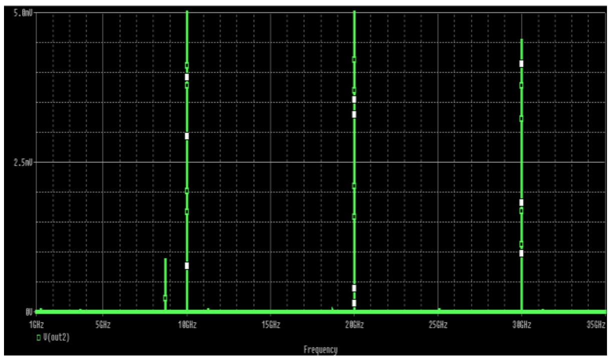

Figure 4.4: Simulated RF output spectrum at 30 GHz

4.3 Up-conversion of RF at 45 GHz

The output spectrum of the HBT mixer using IF at 15 GHz and LO at 30 GHz. The input, LO and output port of the mixer are matched using the impedance values tabulated in table 3. The RF output spectrum obtained in the output probe is shown in figure 4.5.

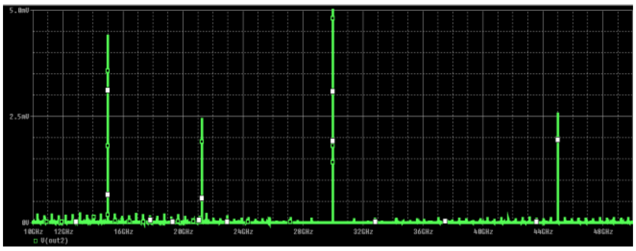

Figure 4.5: Simulated RF output spectrum at 45 GHz.

4.4 Up-conversion of RF at 75 GHz

The output spectrum of the HBT mixer using IF at 25 GHz and LO at 50 GHz. The input, LO and output port of the mixer are matched using the impedance values tabulated in table 3. The RF output spectrum obtained in the output probe is shown in figure 4.6.

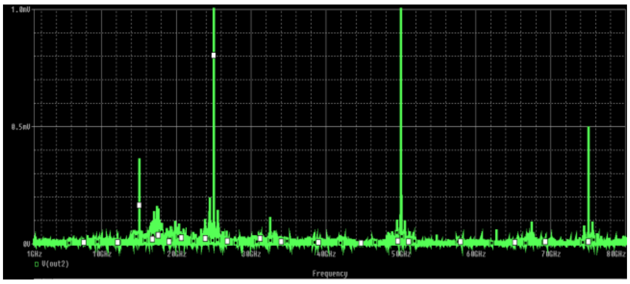

Figure 4.6: Simulated RF output spectrum at 75 GHz.

4.5 Comparison of Conversion losses

Table 4: Conversion gain for different RF signals

Frequency (in GHz)	**Input power (in dBm)**	**Output RF power (in dBm)**	**Conversion gain (in dB)**
IF= 5 LO= 10 RF= 15	IF= -26 LO= 10	-31.4	-4.4
IF= 10 LO= 20 RF= 30	IF= -28 LO= 5	-38	-10
IF= 15 LO= 30 RF= 45	IF= -44 LO= 3	-42	2
IF= 25 LO= 50 RF= 75	IF= -54 LO= 5	-56	-2

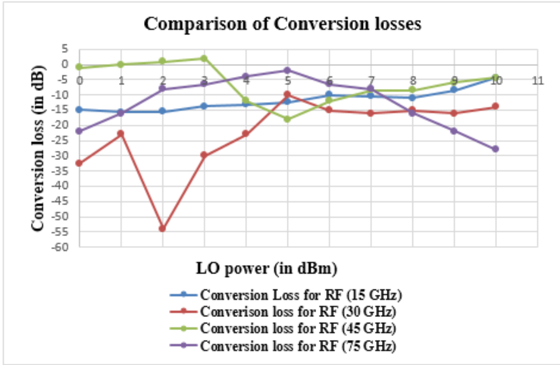

Figure 4.7: Comparison of conversion losses.

A comparison of conversion losses of the mixer operated at different IF frequencies to get the desired RF frequency at different LO power is presented using a graph in figure 5.1. The graph is plotted using the conversion loss/ gain, which is the difference between the inputs IF power to the output RF power obtained after conversion. The conversion loss for RF at 15 GHz increases from LO power of 0 dBm to 2 dBm after that it reduces and maintains a lowest conversion loss at LO power 10 dBm. The conversion loss for 30 GHz is fluctuating till LO power of 5 dBm. Similarly, for 45 GHz it is low till LO power of 3 dBm, we obtain a conversion gain of 2 dB at this point but after that it starts increasing. For, 75 GHz till LO power of 5 dBm conversion loss decreases and after that it starts increasing gradually. The better conversion gain obtained for different RF frequencies are tabulated in table 4.

5. CONCLUSION

IF over fiber has low BER, better Quality factor and high dynamic range than RF over fiber but, the practical difficulty in IF over fiber is that they need up-conversion in the remote base station. Simple and less complex receiver end of the remote base station is the main requirement of RoF systems. Hence, numerous techniques have been introduced for frequency up-conversion in the receiver end.

We have up-converted four electrical signals from IF frequency 5 GHz, 10 GHz, 15 GHz and 25 GHz for RF frequency 15 GHz, 30 GHz, 45 GHz and 75 GHz using a HBT electrical mixer due, to its less complexity, cost effectiveness and extended usage up-to millimeter wave signal range. Better mixing is obtained in the up-conversion of RF at 45 GHz with a conversion gain of 2 dB at a LO power of 3 dBm.

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