King Abdullah University of Science & Technology

Department of Electrical Engineering

EE 242: Digital Communication & Coding

A QPSK Modulator Using Microwave Couplers and Switches for Satellite Transmitter and Its Performance Analysis

Project Report

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1. ABSTRACT

This project reports the design and implementation of microstrip based quadrature phase shift keying (QPSK) modulator using quadrature hybrid (Branchline) coupler, Wilkinson Divider, Rat Race Coupler and MESFET switches. The modulator is designed to operate between 7.9 GHz to 8.4 GHz which is a very common band for remote sensing purposes. Fabricated modulator has carrier suppression of 29 dB across the frequency range and has an amplitude imbalance of less than 1% with phase imbalance of 0.4° around its center frequency. The modulator is checked up to 160 Mbps and spurious suppression is found to be greater than 30 dB and has very low DC power consumption. The project also investigates the effect of amplitude imbalance and phase imbalance on the performance of the modulator. A theoretical relationship has been developed between the S parameters of the circuit elements and the overall performance of the modulator.

2. INTRODUCTION

Several microwave digital communication links employ QPSK modulation as the preferred modulation scheme for terrestrial as well as satellite communications. In satellite QPSK modulation is widely used at X Band for remote sensing purposes. Transmitters designed for this purpose are usually super heterodyne employs modulation at some lower intermediate frequency (IF) and later on up-converted to desire microwave or millimeter wave frequencies. This approach however produces complex and costly transmitter. In modern systems, super heterodyne transmission and reception is replaced by direct carrier modulation or homodyne solution which yields simple, compact and cost effective design in microwave/millimeter wave.
A reflection-type, microstrip based QPSK Modulator is proposed here. QPSK Modulators has been published earlier using reflection topology [1][2], mixer based [3][4] but the design proposed here demonstrates excellent carrier suppression, phase and amplitude imbalances. The design is in the range of X band from 7.75GHz to 8.75GHz with a data rate up to 150 Mbps. This high data rate ensures the transmission of images acquire by high resolution optical sensors subject to visibility of ground station from the satellite. [5]
In this project, a compact microstrip circuit, as shown in figure-1, is presented which utilizes a branch-line hybrid coupler, MESFET switches and rat race coupler to perform QPSK operation. It consumes very low DC power and has very low insertion loss. Use of high speed MESFET switch makes it capable to support high data rate.

3 THEORY

The entire modulator circuit is made of three microwave circuit elements:

i) Wilkinson Divider
ii) Branchline Coupler
iii) Rat Race Coupler

3.1 WILKINSON DIVIDER

Wilkinson divider can be an n-way divider. The simplest form is two-way Wilkinson divider. Two-way Wilkinson divider is a three port circuit element which is used to divide the power of the carrier into two equal parts. Wilkinson divider has a property that it does not generate any phase shift between the two out ports. The two ports are isolated by a 100ohm resistor so that the power from one output port does not couple to the other output port. Wilkinson Divider can be used as a combiner but here we are only interested in its functionality as a divider.

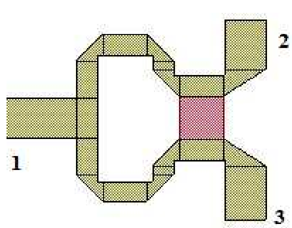
3.2 BRANCHLINE COUPLER

Branchline coupler is also known as the quadrature hybrid or simply hybrid coupler. Hybrid coupler is a four port circuit element use to couple the input carrier to its output ports with a magnitude of 3dB. The above function can be simply termed as power division i.e. the input carrier will be divided into equal components. The difference between Wilkinson divider and hybrid coupler is that hybrid coupler has two inputs compared to one input port of Wilkinson divider and the most important thing is that hybrid coupler provides a phase shift of 90° between the two out ports. The two input ports are isolated from each other hence one can be used at a time. When carrier is launched from port 1 the signal received at port 3 will be lagging by 90° with respect to port 2 and when the carrier is launched from port 4 port 2 will be lagging by 90° with respect to port 3.

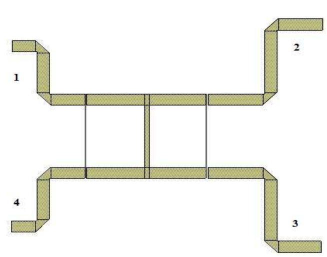
3.3 RAT RACE COUPLER

Rat race coupler widely known as the ring hybrid coupler is also a four port circuit element with two input and two output ports. Here rat race coupler has been used as a three port element as its fourth port (one of the output ports) has been matched to 50ohm. The signal from any one of the input port will couple to the output port with a coupling factor of 3dB or it can be said that the signal from any one of the input port will reach the output with half power as the remaining half will go into the matched fourth port. The signal is launched from port 1 will lead the signal from port 2 by a phase of 180°, which means that ring hybrid can produce a phase shift of 180°. Due to the above mentioned reason ring hybrid is also known as a 180° hybrid.

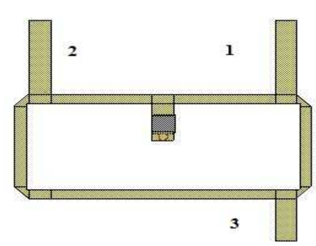
All the three circuit elements can be designed using waveguides, strip line or microstrip but in the project these elements are designed using microstrip technology.



Wilkinson Divider



Hybrid Coupler



Rat Race Coupler

4 DESIGN TOPOLOGY

QPSK modulation is a type of Phase Shift Keying in which carrier is modulated with two data bits from the data stream simultaneously which results in one out of four possible carrier phase states. Thus, the information transfer rate of QPSK modulation is double than BPSK for the same bandwidth. Out of the two streams, one is In-phase and the other is Quadrature, each with symbol rate equal to half that of the incoming bit rate. Both I and Q streams are mixed separately with two Quadrature carriers. This results in two BPSK modulated signals 90° out-of-phase. QPSK signal is obtained by summing the two BPSK signals. Mathematically, the four possible states can be expressed as:

$$S_{QPSK} = \sqrt{2Es/Ts}\,\mathrm{Cos}\{(n-1)\tfrac{\pi}{2}\}\mathrm{Cos}(2\pi f_c t) - \sqrt{2Es/Ts}\,\mathrm{Sin}\{(n-1)\tfrac{\pi}{2}\}\mathrm{Cos}(2\pi f_c t)$$

where n=1, 2, 3, 4

Mentioned four phases can be obtained using controlled microstrip phase shifting structures. The modulator illustrated in this paper is basically phase shifting network obtained through branchline couplers and ring hybrid in which signal flow is controlled by MESFEST switches as shown in figure 1

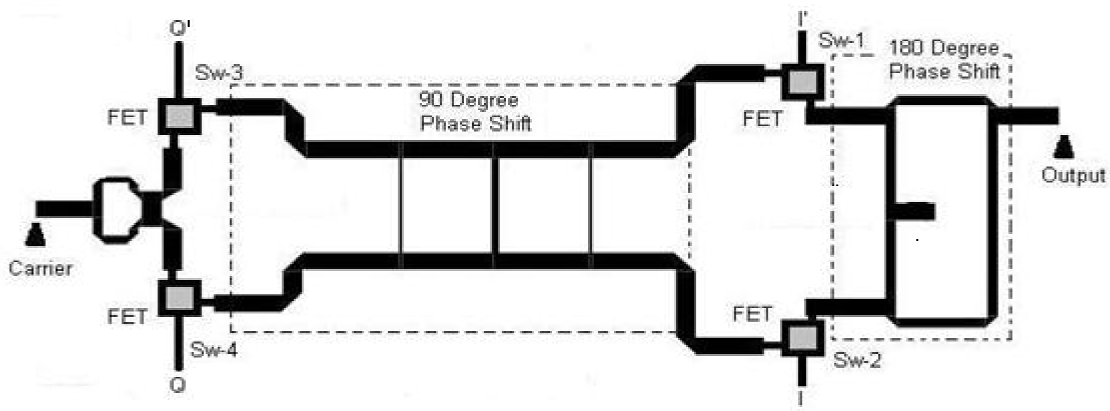


Figure 1: The Design of QPSK Modulator

5 CIRCUIT DESCRIPTION

The proposed QPSK modulator design has merits of reduced size, better carrier suppression and low insertion loss. The modulator topology described in this project is a network of phase shifters realized through transmission lines, Quadrature and ring hybrid (Rat Race Coupler), and controlled by Siemens MESFET's CFY25 used as switches, which in turn, are controlled by the input data bits. These MESFET's are short with Logic 1 corresponding to 0V, and turn open with Logic 0 corresponding to -1.2V. This small transition in voltage also enables fast switching of the transistors. The whole circuit of modulator can be divided into three circuit elements along with MESFET switches operated by I and Q data streams.

5.1 WILKINSON DIVIDER

The 8.25 GHz carrier for modulation is fed into a Wilkinson Divider which is at the input of the QPSK modulator. This carrier is divided into two components equal in magnitude and in-phase. The two components of the carrier are fed to the two ports of branchline coupler. The whole flow of the carrier will be explained in section 5 “Working”. The design of Wilkinson Divider is simulated in a high frequency software AWR’s Microwave Office. The results exhibit an amplitude imbalance of 0.06dB which is almost equal to 0 dB (the ideal case) and phase imbalance of 0.6° which is again very close to 0° (the ideal case). Figure 2 and Figure 3 exhibit the simulated results of S parameters of Wilkinson Divider.

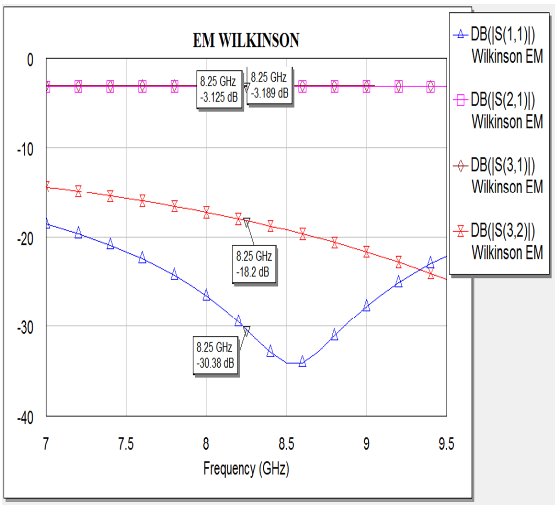


Figure 2: Magnitude of Wilkinson Divider

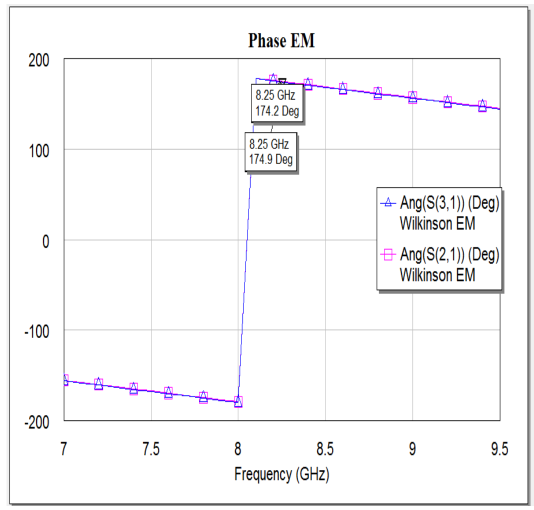


Figure 3: Phase of Wilkinson Divider

5.2 BRANCH LINE COUPLER (Hybrid Coupler)

The Carrier after division from Wilkinson is fed into the two switches controlled by Q and Q’. For any combination of data only one will be allowed to pass through to the input of hybrid coupler, this means that only one of the two input ports of hybrid coupler will receive the signal from previous element. The hybrid coupler will divide the signal into two parts with a phase shift of 90° between them. The simulated results of hybrid coupler depicting the amplitude and phase S parameters are shown in figure 4 and figure 5. The graph demonstrates an amplitude imbalance of 0.055dB which is very close to the ideal case of 0dB. Similar results are observed in the phase plot which indicates a phase imbalance of 90.25°. This is very close to the ideal case where phase imbalance should exactly be equal to 90°.

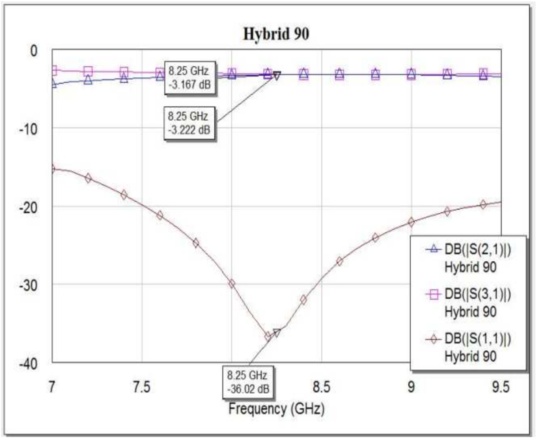


Figure 4: Magnitude of Branchline Coupler

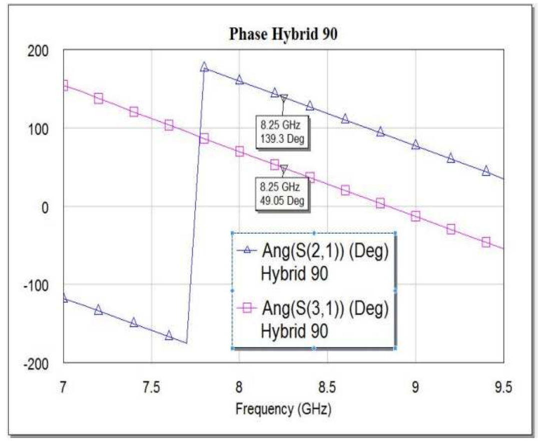


Figure 5: Phase of Branch Line Coupler

5.3 RAT RACE COUPLER (RING HYBRID COUPLER)

The carrier from the output ports of the hybrid coupler passes through the two switches operated by I and I'. The same thing happens with these switches as for the previous two i.e. only one will be operational at a time and the carrier will pass through that switch. The carrier from the switch will be incident on any one of the input ports of the rat race coupler. Rat Race coupler is also simulated in Microwave Office. Figure 6 and figure 7 display the magnitude and phase response of the coupler. Magnitude response shows that there is an amplitude imbalance of 0.049dB again a result very close to the desired result of 0dB where as phase response shows that the phase imbalance is 180.64° which reflects excellent efficiency of the design as the desired value is exactly 180°.

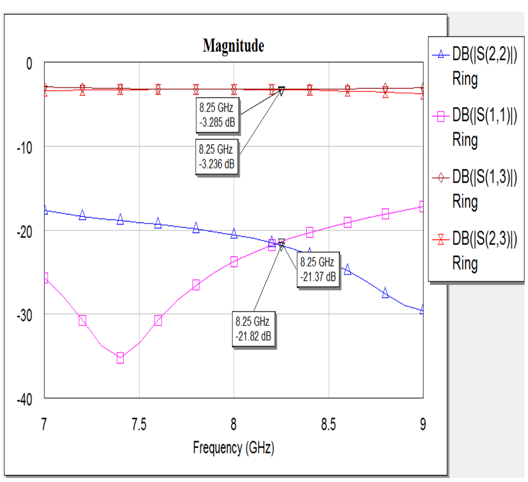


Figure 6: Magnitude of Rat Race Coupler

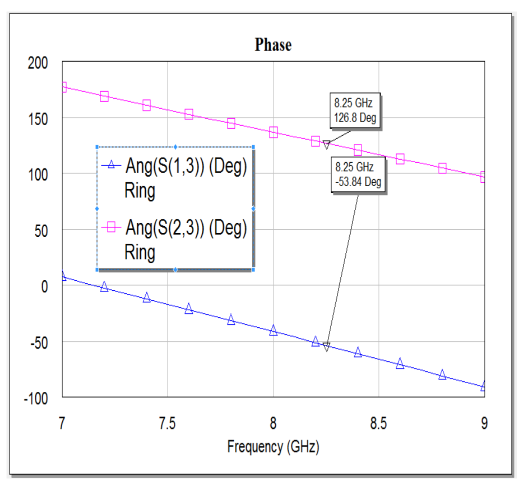


Figure 7: Phase of Rat race Coupler

5.4 MESFET SWITCHES

CFY25 MESFETs have been used as switches to control the flow of signals to the output of modulator. These MESFETs are able to operate up to Ku band. CFY25 requires a pinch off voltage of -1.1V. Signals oscillating between 0 and -1.2 were used control these transistors. Two complementary signal of each channel (i.e. I, I’ and Q,Q’) is required to operate the function of QPSK.

6 WORKING OF THE MODULATOR

Carrier of frequency 8.25GHz is launched from the input port (port 1) of Wilkinson Divider which produces two components of the carrier 3dB down with respect to input i.e. equal split. The output ports (ports 2 and 3) of the Wilkinson are connected to two CFY25 MESFETS working as switches operated by the data streams Q and Q’. The nature of the bit steams suggest that there will be only one of the switches that will allow the carrier to flow through it since if Q is at logic 1 than Q’ will be at logic 0 and vice versa. Both the components will have a zero phase shift among themselves. The component allowed to flow through will be launched at one of the two input ports (ports 1 and 4) of branchline coupler. This coupler will further divide the carrier into two parts of equal magnitude but 90° apart from each other. The two output ports (ports 2 and 3) of the hybrid coupler are again connected to two MESFET switches operated by data streams I and I’. As was the previous case only one of the parts will pass through the switch which is open and will incident on one of the input ports (ports 1 and 2) of rat race coupler. This coupler will either pass the carrier without any phase shift or will produce a phase shift of 180° depending upon which one of the inputs has been used. Now to understand the complete functioning let us consider a symbol say 00. This means that both I and Q are at logic 0 while I’ and Q’ are at logic 1. Referring to figure 1 and figures of the individual elements, Q’ at logic 1 means that the carrier will pass through port 2 of Wilkinson divider and will launch at port 1 of hybrid coupler. I’ being at logic 1 depicts that the carrier will flow through port 2 of the hybrid coupler hence there is no phase shift from the hybrid coupler. The carrier from hybrid coupler will enter from port 1 of the rat race coupler which will again cause no phase shift hence it can be concluded that for symbol 00 there will be no phase shift in the carrier. For 10 the carrier will flow from the port 3 of Wilkinson divider and will enter the hybrid coupler from port 4. Port 2 of hybrid coupler will be active as I’ is at logic 1 and hence the carrier will flow through it but will experience a phase shift of 90° and will then enter the rat race coupler from port 1, so there will be no phase shift due to rat race coupler. Hence overall phase shift will be that of 90° for the symbol 10. Similarly the symbols 11 and 01 will experience phase shifts of 180° and 270° respectively. The following constellation will be obtained due to different phase shifts:

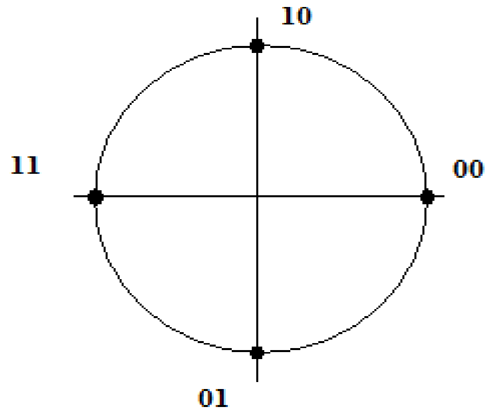


Figure 8: QPSK Constellation

7 FABRICATION, TESTING AND MEASUREMENTS

Modulator hardware as shown in figure-11 has been tested up to a data rate of 160 Mbps (80 Mbps on each I and Q channel). The spectrum obtained exhibits a carrier suppression of greater than 35dB with phase imbalance of less than 0.5° and amplitude imbalance of less than 1% over the range of 7.9 GHz to 8.5 GHz. The modulator is a passive one so it has zero power consumption. Rohde and Schwarz FSQ signal analyzer has been used for testing the circuit. Tables 1 and 2 summarize the results of QPSK modulator at different frequencies and data rates. Figure 9 and figure 10 represents the measured results of the modulator. Figure 9 is the spectrum obtained while testing the modulator at 8.25 GHz carrier frequency and a data rate of 160Mbps. Figure 10 is the constellation diagram obtained under the same conditions. The Constellation diagram shows that the amplitude imbalance of 0.543% of the launched power and phase imbalance of 0.3°. The two imbalances combine give us an EVM (Error Vector Magnitude) of 0.75% which is better than most of the modulators.

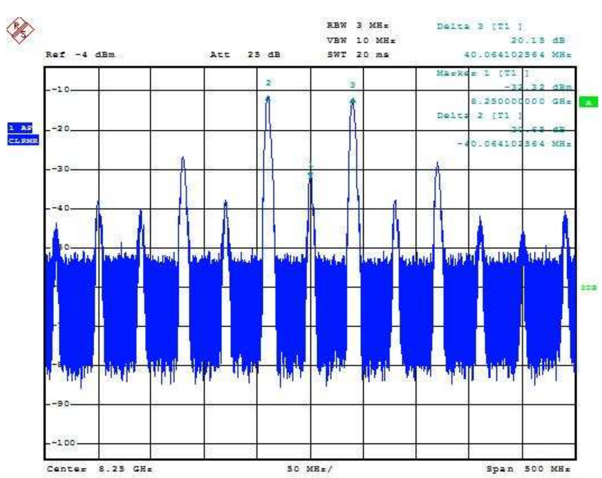


Figure 9: Spectrum of the Modulator

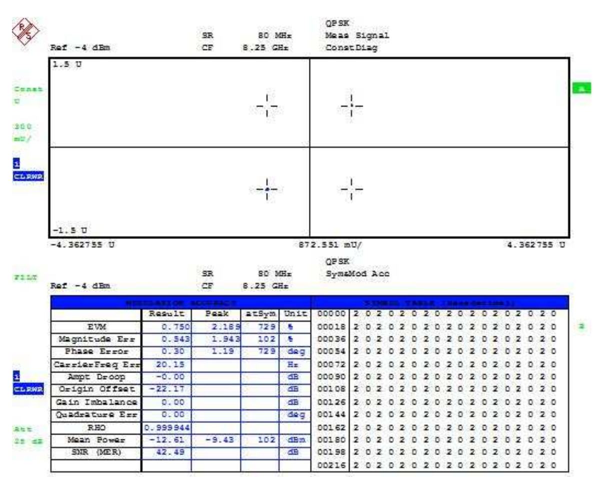


Figure 10: Constellation of the Modulator

Frequency (GHz)	Amplitude Imbalance (%)	Phase Imbalance (deg)	Carrier Suppression (dB)
7.9	0.581	0.36	30.3
8.25	0.543	0.30	32.3
8.4	0.568	0.38	29.8

Table 1: Modulator at Different Frequencies

Data Rate (Mbps)	Amplitude Imbalance (%)	Phase Imbalance (deg)	Carrier Suppresion (dB)
160	0.543	0.30	32.3
120	0.330	0.25	34.4
80	0.251	0.15	37.1

Table 2: Modulator at Different Data Rates

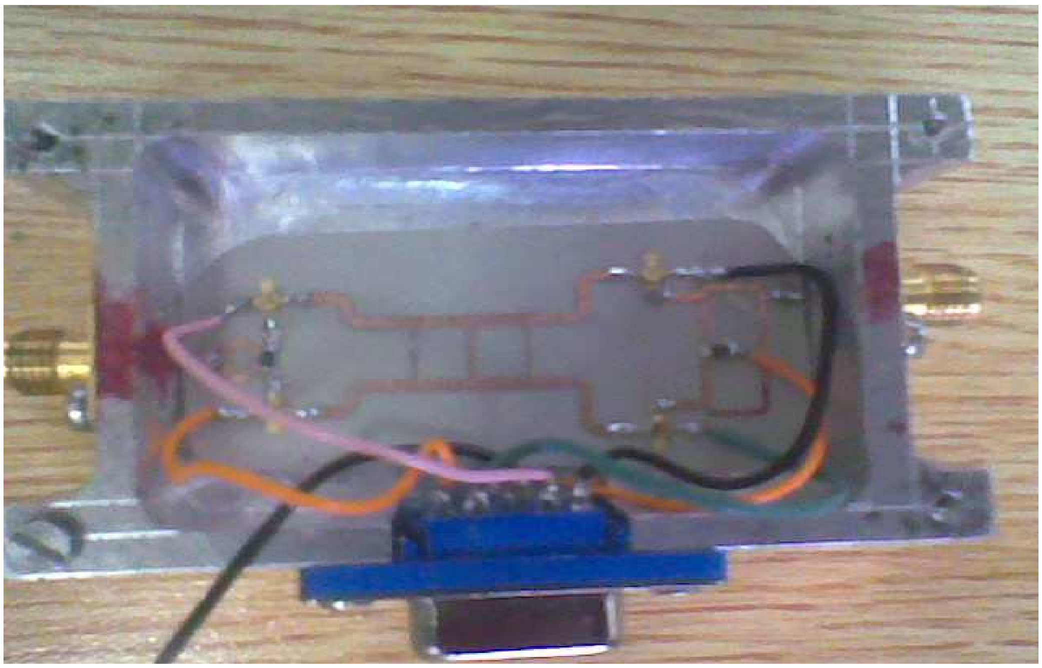
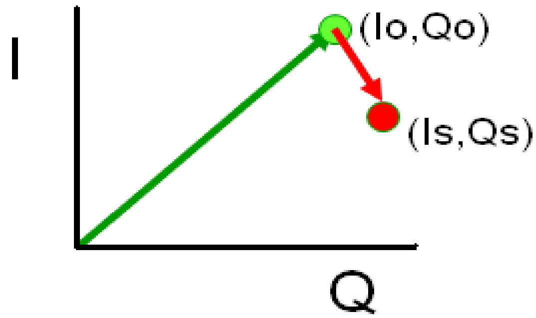


Figure 11: Hardware of the Modulator

8 PERFORMACE ANALYSIS OF THE MODULATOR

The important parameters which effect the Bit error rate of the modulator are the phase imbalance and amplitude imbalance of the modulator. The two combine together give us the term known as Error Vector Magnitude (EVM). EVM is the magnitude of the vector that joins the received symbol and the nearest symbol on the constellation already defined by the transmitter. This can be illustrated by the following diagram:



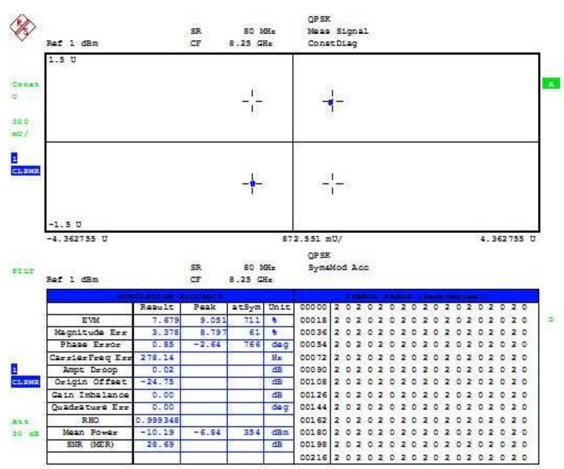
In the figure to the left the vector drawn with red colour is the vector whose magnitude will be referred to as EVM. I_o and Q_o represents the constellation point already defined at the transmitter end while I_s and Q_s represents the symbol received.

The designed modulator has an excellent EVM values at different data rates. Table 3 gives the values of EVM when the modulator is tested at 8.25GHz carrier frequency and at different data rates:

Data Rates (Mbps)	EVM (%)
160	0.750
120	0.479
80	0.368

Table 3: EVM values at different Data Rates

The important thing is that EVM is a parameter measured after the integration of modulator with the power amplifier. Power amplifier is the module that adversely effects the EVM of a system. The modulator has been tested with the power amplifier and demonstrates the following results:



The figure above shows that after integration with the power amplifier the value of EVM degrades from 0.543% to 7.479% but still the value is under the desirable range. For most of the transmitter studied it has been observed that EVM has to be kept lower than 20%. If the value of EVM is under 20% than the design of the modulator is quite efficient. This is because the value of EVM for whole transmitter is dependent on the modulator. The better the EVM of the modulator better will be the performance of the entire system. In order to keep the EVM (amplitude and phase imbalance) under the desired value it is very important that the elements of the modulator should be optimized to their best. The S parameters are the measure which can define whether the amplitude and phase imbalances or we can say the EVM is under control or not. For example for Wilkinson we will want that there is zero phase shift between the two output ports while for hybrid and ring hybrid it should be closely observed that the phase shift should be equal to 90° and 180° respectively. This will control the phase imbalance of the entire modulator.

Similarly the magnitude response of the elements should be optimized so that it produces minimum amplitude imbalance. Wilkinson should be designed so that the output ports have minimum amplitude imbalance (should be close to 0dB). The same criteria should be followed for the designing of the other two elements i.e. branchline coupler and rat race coupler. If these S parameters are optimized as described above then the modulator will have minimum amplitude and phase imbalance and hence the minimum value of EVM. Following graph illustrates EVM of QPSK versus BER (bit error rate).

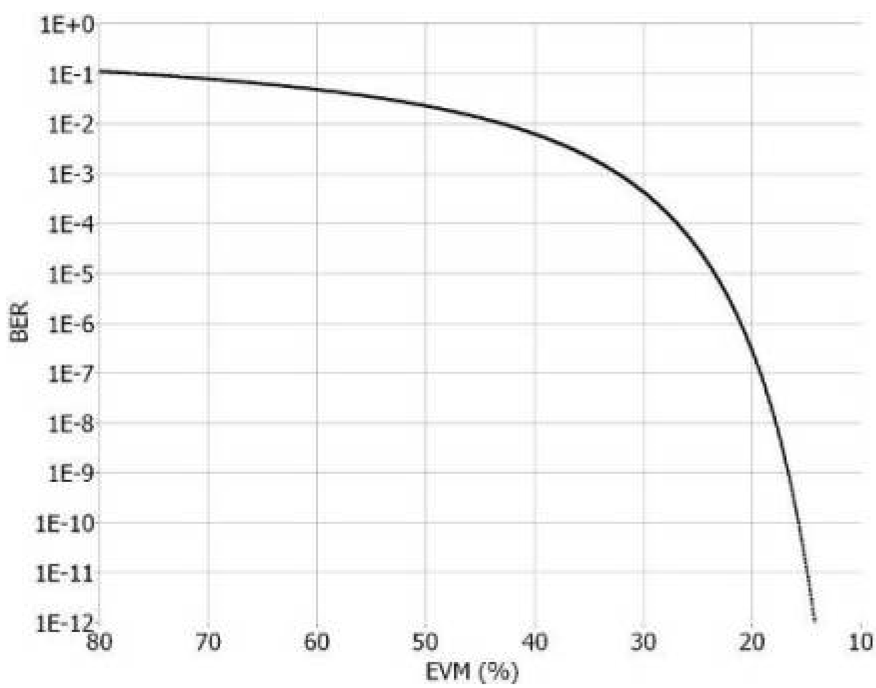


Figure 12: BER vs. EVM of QPSK [9]

The graph above shows that by keeping EVM lower than 20% it will be possible to achieve a bit error rate of less than 1e-6 which suggests excellent efficiency of the system. One more thing that has to be kept in mind is that the modulator's efficiency will decrease with the increase in data rate. As it is obvious from table 3 that the best results of the modulator are obtained when working at a data rate of 80Mbps, increasing the data rate will cause amplitude and phase imbalance to deteriorate which will effect the EVM of the system and hence effecting the bit error rate.

8.1 EVM AND SNR

EVM can be related to SNR using the following formula

$$\text{EVM } \alpha \frac{1}{\sqrt{SNR}}$$

Now probability of error of QPSK can be given as:

$$P_e = 2Q\left(\sqrt{\frac{2E_b}{N_0}}\right) - Q^2\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

$$\text{where SNR}=\frac{E_b}{N_0}$$

The above equation suggests that lesser the EVM greater will be the SNR and hence lesser the value of Q. The above mathematical equation concludes that lesser the EVM lesser will be the probability of error.

9 CONCLUSION

The simple, compact, and low cost QPSK modulator designed and presented in this paper exhibits excellent results of carrier suppression, amplitude imbalance, phase imbalance and hence EVM. It has reduced size and can support extremely high data rates without any degradation in performance and can work efficiently in a bandwidth of 1GHz. The modulator has been designed keeping in mind minimum bite error rate in order to provide excellent performance of not only the modulator itself but also the entire transmitter when the modulator is integrated with the amplifiers and filters. In order to keep the EVM of modulator less than 1% it has been kept in mind that the individual elements show the best of their S parameters. Lower the value of EVM of the modulator greater will be the SNR and hence lesser will be the probability of error. The modulator has been tested with the help of FSQ26 Vector Signal Analyzer of Rohde & Schwarz. It has been integrated with the power amplifier which works at an output power of 2Watt which is 33dBm. The modulator thus designed is suitable to be operated for remote sensing purpose keeping in mind its electrical functionality.

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