Microwave/mm-wave Components & Technology for Point-to-Point Digital Radios in Cellular/PCS Applications

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Introduction:

The wireless revolution has created a number of new opportunities for microwave technology. Point to point radios are now being used to connect cellular and PCS cell sites with the central switching station as well as for private data links. With the saturation at frequencies below Ku band, 15,18,23 & 38 GHz radio bands have emerged as internationally accepted bands for the emerging wireless applications. Actual selection of frequency is dependent upon climate, country regulation & present use of microwave radios. These radios however need to be cost competitive to leasing equivalent wireline capacity from the local telephone or cable TV company for being successful in the urban areas. With the ever changing communication demands, what customers are looking for includes: flexible hardware that allows them to buy and re-configure as they grow, reliability and they want it fast. With increasing demand of the radios due to rapid deployment of cellular/PCS systems as well as increasing market price pressure the radio & component manufacturers have a hard & challenging task in order to release competitive & performing products.

In order to produce radios for this huge need, low cost, user friendly and high performance components at microwave /millimeter wave frequencies are a basic necessity. Fortunately, with the reduced demand of microwave & millimeter wave components for the military market the technology & competence developed for that purpose can be effectively put to commercial communication use in a timely fashion. A number of companies are presently involved in this transition. The most expensive components are transmitter & receiver at these frequencies. This paper will describe different approaches used in the transmitter & receiver design of these radios. A unique approach optimizing the use of silicon and GaAs technologies for a high performance and cost competitive solution for the Tx & Rx is presented. Components & technology developed for Tx & Rx for 23 & 38 GHz radios for applications as short haul radios as backbone interconnect terminals for Cellular & PCS applications will be described. Major issues related to the need for technology in the future will be addressed.

Frequency Bands:

Presently the frequency bands used internationally for applications to interconnect the cellular & PCS base stations are shown in the table below. The selection of frequencies for a particular application depends upon many variables including geographical location, regulatory issues, required range coverage & interaction with existing microwave radios for other applications. As an example while 23 & 38 GHz are commonly used frequencies in western Europe, 15 & 18 GHz are more popular in developing countries like India & eastern Europe. Lower frequencies (13,15 GHz) are generally preferred for areas prone to heavy rains in order to reduce the effect of rain attenuation on the link performance. In addition to the bands listed below there are few more bands with limited applications at frequencies of 29, 50 & 55 GHz.

Frequency Band	Power Out
37-40 GHz	18 dBm
24.5-26.5 GHz	18 dBm
21.2 - 23.6 GHz	19 dBm
17.7-19.7 GHz	20 dBm
14.2 -15.35 GHz	20/23 dBm
12.75-13.3 GHz	20/23 dBm
10.7-11.7 GHz	20/23 dBm

Table 1 : Frequency Bands & Tx Power Output

Data Rates & Modulation Schemes:

The data rate requirements for these short haul low capacity radios vary from 1.5Mbits/s to 45 Mbits/s. A number of modulation schemes are presently used for the PCN/Cellular digital radios. This includes 4L FSK, QPSK, OQPSK & CPM. One of the commonly used modulation schemes presently is 4L FSK which allows the radio manufacturers to use relatively lower cost components compared to more complex modulation schemes. Main difference between the technology requirements for different modulations is in the area of power amp linearity & phase noise for L.O./Tx. A 4L FSK Tx can use saturated amplifiers compared to a > 3 dB back off from P-1 dB required for a QPSK Tx and >10 dB back of for higher levels of QAM modulation schemes. These back off levels can in some cases be improved by using sophisticated forward error correction techniques. A 4LFSK Tx can operate easily with -80dBc/Hz (@ 100 KHz) phase noise Tx, while a QPSK Tx will need about 10-12 dB lower & a 16QAM Tx even better phase noise for comparable performance. Even though there is a significant difference between the spectral efficiencies of the different approaches, it seems that 4LFSK will continue to be a dominating modulation scheme for quite some time for these applications due to cost reasons. There also exists a need for high capacity (155Mbits/sec, 622Mbits/sec & 2.5Gbits/sec) radios for compatibility with fiber optic communication systems for applications at different points in the telecommunication infrastructure networks. These radios will need more complex modulation schemes like 16QAM, 64QAM or higher in order to achieve the spectral efficiencies required.

Components & Technology for Transmitters:

Block diagram for the point-to-point radios depends upon various factors including modulation scheme and available technology. For example there are two architectures for transmitters:

a) *Block Upconverted Transmitter:*

This approach is shown in figure 1 below. In this case a modulated signal, generally anywhere between 2 to 4 GHz is upconverted to the final frequency, filtered and amplified. This approach can be used for 4LFSK as well as for QPSK/QAM schemes. The IF frequency limits bandwidth of the transmitter. Higher IF will make the filtering and hence meeting the spurious specs easier but would increase the cost of the transmitter. In this approach the communication band is generally covered in two bands. L.O. phase noise and power amplifier linearity is defined by the modulation scheme. In case of modulation requiring linear amplifier, the output power control can be implemented at the IF section.

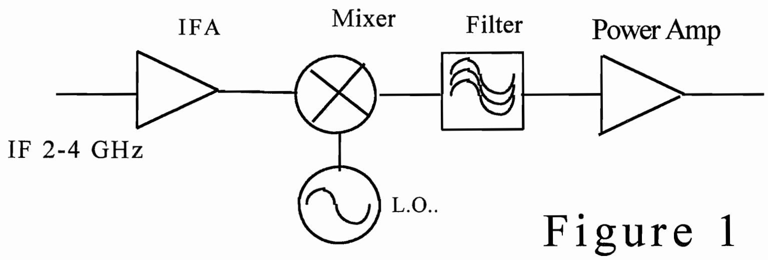

Fig. 1 Transmitter Block Diagram

b) *Direct Modulation Transmitter:*

This approach shown in fig. 2 is a VCO based Tx in which a fundamental VCO at the final or subharmonic of the desired radio frequency is directly modulated through the tuning port. This approach is typically used for the 4L FSK modulation radios. Full communication band can be easily covered using this approach. The performance requirements on the PA & phase noise are significantly different in the two systems shown above. The components and technology reported in this paper correspond to the direct modulation transmitter approach.

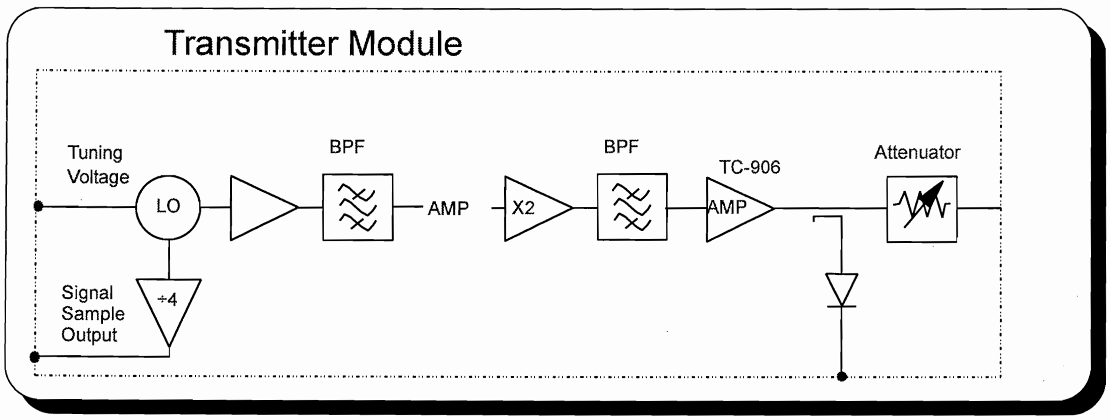

Fig. 2 VCO based Transmitter Configuration

The Tx source is typically the most expensive RF component in the system. A number of different approaches have been used in the transmitter design of radios above 18 GHz. The most common approach has been the use of fundamental Gunn Oscillators. Till recently the three terminal device technology, though available for years have not been cost competitive with the Gunn solution. Gunn oscillators have inherent problems of microphonics, cold start, consistency, mechanical tolerance requirement, DC power, space and weight requirement. Additionally multiple Gunn oscillators are required to cover the full band. Gunns however have excellent phase noise and can generate the required 17 to 20 dBm power using a single device. GaAs MMIC prices at mmw frequencies have now come down to be an attractive alternative. A recent approach used a fundamental GaAs MMIC VCO with dual varactors, but has inadequate phase noise and linearity for easy application in the 4 level FSK modulation scheme. Fundamental oscillators have an additional disadvantage of requiring complex harmonic sampler based phase locking techniques.

In our unique approach optimum use of silicon and GaAs technologies has been made to achieve high performance and cost competitive solution for the Tx source at 23 & 38 GHz (figure 1).

This source simultaneously provides an L-Band signal in addition to the final frequency. A low phase noise C-Band VCO with two outputs feeds a GaAs FET frequencymultiplier to generate X/Ku-Band signal and a silicon divide by four MMIC Prescaler to generate L-Band signal to be used for phase locking. A GaAs PHEMT frequencymultiplier is used to convert X/Ku-Band signal into K/Ka-Band. A high gain 20 dBm power MMIC represents the output amplifier stage. Bias of this device is switched off to provide mute control. A PIN diode attenuator at the output allows to control the output power by more than 30 dB. A diode detector in the output provides a power monitor feature. The main features of the 23 & 38 GHz sources are:

- ° Availability of L-Band signal for phase locking the source to the reference frequency.
- ° High isolation of the oscillator frequency from load due to freq. converters & MMIC.
- ° Freedom from microphonics & thermal issues compared to the Gunn cavity oscillators.
- ° Low phase noise of silicon bipolar VCO and optimized use of frequency converters.
- ° High linearity single diode tuning characteristics for efficient data transmission.
- ° Single source to cover the full bandwidth of 21.2 to 23.6 or 36 to 40 GHz.
- ° Output power control of more than 30 dB, mute control with >50 dB isolation & output detector for power monitoring.

<u>Oscillator & Frequency Divider</u>:

The basic VCO has been selected to be in the C Band to optimize the following variables:

a) availability of low cost frequency dividers.

b) ease of manufacturability

c) minimize the order of frequency multiplication of the VCO output.

As an example the 4.5 to 5 GHz VCO is the main element of the 38 GHz source module. The challenge is to provide a low phase noise and high linearity VCO to cover the complete communication band. An HP Silicon bipolar transistor AT42000 in conjunction with a high Q linear varactor from Frequency Sources has been used. The varactor diode is used in the emitter terminal of the transistor and a reactive compensation circuit is used to linearize the tuning sensitivity. Power output of 10 dBm has been obtained over 4.5 to 5 GHz. Phase noise at 100 KHz was measured to be -105dBc/Hz. Tuning linearity was measured to be better than 1.1:1 over the communication band. An HPIFD 53153F silicon static Frequency Divider by four is used on the second RF output port, lightly coupled to the VCO. This prescaler useful upto 5.5 GHz in chip form requires only -10 dBm and provides -5 dBm power output at one fourth of frequency.

<u>Frequency Multipliers</u>:

For the 38 GHz Tx two frequency multipliers were used: Times four multiplier for 4.5 to 5 GHz input and times two multiplier for 18 to 20 GHz input. The first multiplier is an HP PHEMT M175 with 0.25μm gate length and 150μm gate width, fabricate don MBE material. An open stub of electrical length of 90° at 4.75 GHz was connected to the drain for blocking the fundamental frequency mode while simultaneously presenting the necessary drain reactance for maximum gain. A highly selective band pass filter was used in the output to eliminate the undesired harmonics. A conversion loss of about 8-10 dB was obtained.

A second frequency multiplier uses an HP GaAs PHEMT M179 with a sub 0.15μm gate length and 200μm gate width, fabricated on MBE material. The device has an f_t of 70 GHz and f_{max} of 120 GHz and the device is capable of delivering 15 dBm of linear power with 9 dB of gain at 20 GHz. The device has a high non-linear transconductance that is adequate for generation of high order harmonics once the bias and matching circuits are optimized. A highly selective band pass filter was used in the output to eliminate the undesired harmonics. A conversion loss of <3dB was achieved for times two multiplying of the18 to 20 GHz signal. Phase noise of the Tx at 40 GHz was measured to be better than -85 dBc/Hz @ 100 KHz.

Power MMIC:
An HP GaAs 20-40 GHz MMIC TC906 a 4-stage amplifier, designed on a 0.25µm-gate PHEMT production IC process was used to provide 20 dB gain and greater than 20 dBm saturated power 3. A traveling-wave-input / power-combined-output scheme used in the first stage using two 120µm FETs has resulted in an area efficient broadband amplifier design. The second, third & fourth stages are 240µm, 360µm and 450µm FETs respectively. A reactive output match provides optimum load for max. power across the band. Important parameters of the chip are as follows:

Frequency Bandwidth	20 - 40 GHz
Gain	> 20 dB
In/Out Return Loss	< - 8 dB
P_o (-1 dB)	>17 dBm
P_o Sat	> 20 dBm
Bias	5V, 300 mA; -0.4V
Size	1.76 X 0.8 mm^2

A PIN diode attenuator in the output provides a means to control the power output by 30 dB. A diode detector is connected through a coupler in order to provide the power monitoring and in some cases a closed loop power output control as needed by the system. Typical performance results of these transmitters at 23 & 38 GHz are shown in Appendix 1.

Components & Technology for Receivers:

Typical receiver block diagram is shown in figure 3 which represents a modern mmw receiver incorporating a low noise LNA. However in order to reduce the LNA contribution to the noise an image reject mixer needs to be employed. The requirements on the linearity of LNA, mixer & LO phase noise are dictated by the modulation scheme used. Once an LNA precedes the first down-converter, the requirements on the mixer are not as stringent as they are in an unbuffered system. It is important to keep the noise-figure of the receiver as low as possible, as this front-end value ultimately determines the threshold level of the receive channel and the overall sensitivity of the radio system. The desired frequency bandwidth can be covered in one or two bands depending upon the system requirements of flexibility of T/R spacing and IF.
A low noise at the front end not only improves the overall system noise figure but also provides a highly desirable consistency for high volume manufacturing. A good LNA can provide enough

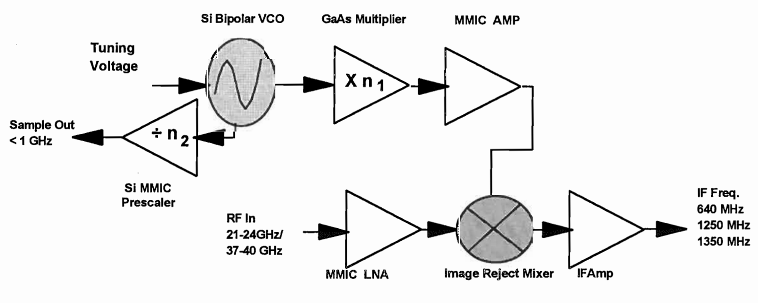

Fig. 3 Receiver Downconverter Block Diagram

isolation between the mixer and diplexer/antenna without the need of an expensive isolator. An HP PHEMT MMIC TC904 is used at 23 GHz and a newer HP PHEMT MMIC "Hush" in development at MWTC is used for the 38 GHz band. These devices provide state of the art performance at competitive prices for use in this critical application. TC904 offers typically a 3 dB noise figure and 22 dB gain across the 23 GHz band while the Hush chip offers about 5 dB NF and 20 dB gain over 38 GHz band.

Mixers:

Image Rejection is necessary when an LNA is used in the down-converter. Image rejection can be achieved by using either a bandpass filter or by using an image reject mixer (IRM) as shown

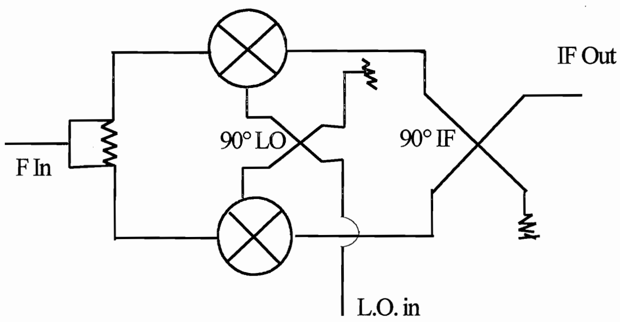

Fig. 4 Image Reject Mixer

in figure 4. IRM Mixer is an attractive option as it is universal in nature and does not depend upon the filtering requirements of any particular system configuration. In the down-converter under consideration, hybrid IRMs have been used in order to achieve the desired rejection of 14 dB at 23 GHz and 12 dB at 38 GHz. The balanced mixer is a rat race mixer the layout of which is optimized over each communication band. RF input is applied to the two identical single balanced mixers, and the LO is applied via a 90 deg hybrid in order to achieve the two IFs 90 deg out of phase. IF 90 deg hybrid which is a modification of a lange coupler helps cancel the image signal and re-combines the desired rf signal.

Local Oscillator:

The L.O. configuration is similar to the transmitter. The VCO frequencies & multiplier ratios (n1) were optimized to eliminate interference between the selected IF frequencies and the divide by output frequencies. The LOs used multipliers by three & two for 23 GHz and three & three for 38 GHz, which required optimization of the bias & matching circuits. Power output of 14 dBm at 23 GHz and 17 dBm at 38 GHz are used to bias the image reject mixer. Phase noise of better than -85 dBc/Hz at 100 KHz offset has been achieved at 40 GHz to help meet the system requirements of the 4L FSK digital radio links.

IF Amplifier:

A low noise HP silicon IF amplifier MSA1100 is used as IF amplifier. It has a gain of >10 dB at the IF frequencies up to 1350 MHz and has a noise figure of 5 dB. P-1 dB of this amplifier is better than 13 dBm.

All the mm-wave/microwave components are packaged in a single enclosed mechanical housing which helps reduce the interface problems created when separate components are used. Resulting better match helps the manufacturability of the radio system. Overall typical performance of the receiver down converters at 23 GHz and 38 GHz is presented in appendix 2.

Future Direction of Components:

The growth in the wireless (cellular, PCS & private links) market is a driver for the high volumes and lower prices for the components described in this paper. In the future the components manufacturers are going to see an intense pressure for delivering just enough performance at the lowest possible cost. Significant effort is expected to be devoted into the following areas to be competitive in the new market:

a) MMICs technology

The volume of components being projected for these applications justify the development of MMICs for these applications. However the challenge is to define the optimum integration level, specifications and configuration to make these devices as universal as possible to justify the investment. HBT IC technology work is in progress at HP Labs & MWTC which should allow us to design VCO with built in dividers and buffers. Improved PHEMT processes should enable us to design multipier, amplifier and attenuator functions in a single chip. On the receiver side new MMICs required, include mixers with built in LO buffer amplifiers.

b) Low cost packages / technologies to 40 GHz

Low cost surface mount packages are key to develop cost effective mm-wave components. Packages are available in the market up to 26 GHz and a significant effort is going on to develop 40 GHz packages. At millimeter wave frequencies, the technology being used today is thin film chip and wire. This technology is labor intensive and not as cost effective as components using softboards an packaged devices. Major challenge today is availability of packaged discrete devices which operate satisfactorily at frequencies up to 40 GHz. Eventually some balance of the hybrid technology and softboard/packaged technology will be used to optimize the performance and cost. Thick film technology needs to be explored to find cover some spaces in the architecture where it can add value.

c) Components for High Capacity Radios:

For low capacity short haul radios spectral efficiency is not a major issue. The high capacity high frequency radios are expected to compete or complement the fiber optics systems in the future. These radios will demand high levels of QAM or even the newer coded modulation schemes like Trellis Coded Modulations (TCM) and Multilevel Coded Modulations (MLCM). These schemes will need higher output transmitter power of the order of few Watts and the phase noise of LO for up and down-converters significantly better than what the radios are using today.

Acknowledgments:

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Appendix 1

Millimeter-Wave Transmitter Module

PRELIMINARY ELECTRICAL CHARACTERISTICS (T_{Flange} = 25 °C)

Part Number		CTM-23			CTM-38		
PARAMETERS	UNITS	MIN	TYP	MAX	MIN	TYP	MAX
RF Tuning Range	GHz	21.2		23.6	37		40
Operating Temperature Range	°C	-30		70	-30		70
RF Power Output	dBm	19	20		18	19	
Sample Out =$RF_{OUT} \div n$	GHz		<1.5			<1.5	
Detected Out	mV	0.5		1.5	0.5		1.5
Harmonics and Sub-Harmonics from 2.65 to 50 GHz from carrier	dBc			-30			-30
Spurious Output	dBc			-60			-60
Phase Noise @ 100 KHz	dBc			-80			-78
Tuning Voltage Vdc @ Fl Vdc @ Fh Vdc Max	 V V V		 1 14 	 16		 1 14 	 16
Input Capacitiance, Nom	pf		27			27	
Main Tuning Sensitivity Variation			1.5 : 1			1.5 : 1	
Modulation Bandwidth	MHz		20			20	
DC Circuit Power 12 Volts 5 Volts -5Volts	 mA mA mA			 200 600 50			 200 600 50
Case Size	inches		3.25 x 1.25 x 0.40			3.25 x 1.25 x 0.40	
Mute Control	dBc		-50			-50	

Note:
1. All parameters are guaranteed over the operating temperature range expect where specified.
2. Integral attenuator with 30 dB attenuation range available. This option adds 400 mA of current @ +5V

Appendix 2

Millimeter-Wave Receiver Down Converter Modules

PRELIMINARY ELECTRICAL CHARACTERISTICS

Part Number		CRMXXXX-23			CRMXXXX-38		
PARAMETERS	UNITS	MIN	TYP	MAX	MIN	TYP	MAX
RF Tuning Range	GHz	21.2		23.6	37		40
IF Frequency	GHz	630, 1260 or 1350 MHz			630,1260 or 1350 MHz		
IF Bandwidth	MHz	±20			±20		
LO Frequency	GHz	RF - IF			RF - IF		
Gain	dB	19		26	18		24
Gain Flatness over 300 MHz	dB			±0.5			±0.5
Noise Figure @ 25°C	dB		4.5	5.5		6.5	7.5
Operating Temperature Range	°C	-30		70	-30		70
Power Input at P-1dB	dBm	-22	-17		-22	-17	
LO Leakage at I[3]	dBm			-15			-15
LO Leakage at R[4]	dBm			-20			-20
Return Loss RF Port	dB	12			8	10	
Return Loss IF Port	dB	14			14		
Image Rejection	dB	12	15		10	13	
Sample Out = (RF - LO) ÷ n	GHz		<1.5			<1.5	
Spurious Output[5]	dBc			-60			-60
Phase Noise @ 100 KHz	dBc/Hz		-85	-82		-83	-78
Tuning Voltage Vdc @ Fl Vdc @ Fh	 V V	 1 		 12	 1 		 12
Input Capacitiance, Nom	pf		27			27	
Main Tuning Sensitivity	MHz/V		300	400		400	500
Main Tuning Sensitivity Variation			1.5 : 1			1.5 : 1	
DC Circuit Power 8.5 Volts 5 Volts -5 Volts	 mA mA mA		 220 240 20	 280 320 30		 270 4701 20	 350 650 30
Case NTE	inches	3.5 x 1.25 x 0.40			3.5 x 1.25 x 0.40		
Connectors			OSM or WR42			WR 22[6]	

Note: 3. LO and Harmonic / sub-harmonic leakage at I with RF terminated into a 50 ohm load.
4. LO and Harmonic / sub-harmonic leakage at R up to 50 GHz.
5. Measured at IF port within the IF bandwidth with single tone RF input of < -20 dBm.
6. WR 19 also available.