MILLIMETER-WAVE AUTOMOTIVE RADARS AND RELATED TECHNOLOGY

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ABSTRACT

Automotive Radars are rapidly moving from R&D to the pre-production phase. The market opportunity is unprecedented. However, the cost targets require a transformation of the millimeter-wave industry from high performance, expensive prototype designers, to low-cost consumer product manufacturers. This paper will compare waveguide, hybrid and monolithic solutions based on performance and cost trade-offs.

INTRODUCTION

Millimeter-wave (MMW) Automotive radars are hopefully moving to production. Large manufacturing margins are necessary to ensure high yield production runs. The MMW front-end, includes the Transmit-Receive (T/R) functions at 77 GHz and due to the very high frequency of operation, it is the most critical part of the system. The key component in the front-end, the oscillator, is still facing many challenges. This article will focus on the device technology available to address the transmitter oscillator requirements in production.

REQUIREMENTS

The two most critical transmitter oscillator requirements, phase noise and output power (see Table 3) are dependent on the system configuration. Only FMCW and Pulsed radars will be considered. FMCW system, being FM modulated, requires the least output power. Due to its homodyne approach, the phase noise requirements are very critical. Its simultaneous T/R operations require a circulator (or worse two antennas). This device limits the T/R isolation and adds cost. In addition, to achieve good distance resolution, the FMCW approach requires a linearization circuit. The pulsed system, for the same range, requires more output power, but the phase noise is not as critical. The on-off modulation is realized with a high speed switch, which takes the place of the circulator. Regardless of the system configuration, the output power required at the antenna flange is dependent on the antenna design. Because more than one beam is required, the insertion loss, from the source output to the antenna port, increases with the number of feeds. The switch matrix in front of the antenna increases the insertion loss by around 3 dB. An alternative antenna configuration that doesn't require the switch matrix is realized by a mechanically scanned single beam solution. Furthermore, additional circuitry between the oscillator output and the antenna input will add a couple of dB loss, bringing the overall loss with and without the switch matrix to 5dB and 2 dB respectively. To make the entire system affordable, the front-end cost, in large quantities (see Tables 1 and 2) needs to be $70 or less, with the transmitter oscillator active device costing no more than $20.

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Chip	Size	Cost	Chip Cost
TX (PHEMT)	5mm^2	\$4/mm^2	\$20
SP3T(PINs)	1.5mm^2	\$2/mm^2	\$3
Total			\$26

Table 1. MMIC Cost

MMICs	\$26
Housing and materials	\$10
Loaded Material	\$36X1.6=\$57.60
Assy/Test (\$60/Hr)	\$60X0.20=\$12
Total	\$69.60

Table 2. Transceiver Cost

	FMCW with switch matrix	FMCW w/0 switch matrix	Pulsed with switch matrix	Pulsed w/0 switch matrix
Pout (dBm) at antenna port	10	10	13	13
Pout (dBm) at oscillator output	15	13	18	16
Phase Noise (dBC/Hz) @ 100 KHz	-80 min	-80min	-65min	-65min
Band (GHz)	76- 77	76-77	76-77	76-77

Table 3. Transmitter Electrical requirements

GaAs AND InP GUNNS

Gunn diode oscillators use the negative resistance property of bulk GaAs or InP. These devices are usually used in a wave-guide cavity that optimizes their phase noise behavior. Planar designs, which are more suitable for integration with microstrip components, are also possible. GaAs Gunn diodes are fabricated from epitaxial layers grown by VPE techniques. MBE and MOCVD can also be used to increase reproducibility. At 77 GHz, GaAs diodes do not easily produce power at the fundamental frequency and the oscillator is typically designed as a second harmonic device. For that reason, GaAs diode oscillators are, at these frequencies, power limited. A reasonable oscillator power level in production at 25°C is 17dBm at 77 GHz. At higher temperatures, the output power degrades by approximately -.030dB/°C. Assuming a maximum temperature of +95°C, we will lose around 2 dB and an additional 2 dBs will be lost in the resonator and coupling circuitry. Therefore, the power available from the oscillator is 13dBm at 95°C. More output power is obviously achievable by using two diodes in parallel, but the cost and reliability will deteriorate. The phase noise characteristics are excellent and, at 100 KHz off carrier, better than 80dBC/Hz is achievable. In terms of cost, these diodes are reasonably inexpensive and for volumes of 100K or larger, the target price of \$20 is achievable. On the negative side, some cold start problems and microphonic issues require attention during the design phase. Because of their poor efficiency (around 1%), special attention has to be paid to their heat-sinking which greatly affects the reliability. InP Gunns have been primarily utilized and optimized for low volume expensive military applications. InP Gunns are capable of generating power at 77 GHz in the fundamental oscillation mode. Levels of 100mW (20dBm) are achievable at 25°C. In addition, an InP diode does not degrade as much as a GaAs diode over temperature. Assuming a temperature coefficient of -.02dB/°C and the same 2.0dB loss in the resonator and coupling circuitry, a power level of 17 dBm over temperature is achievable. Unfortunately the diode fabrication process is difficult and only a few suppliers exist world-wide. Because of their fabrication complexity, their price is high and a price of \$20, even in large volume, will be very difficult to achieve. Phase noise characteristics are excellent even if the same concerns as for GaAs diodes exist for cold starts and microphonic issues.

MONOLITHIC SOLUTIONS

MMIC solutions [1], [2] could be based on MESFET devices with a 0.25μm gate length, PHEMT devices with 0.25μm or 0.1μm gate length or HBTs with 1μm base thickness. The most critical step in the manufacturing process of monolithic devices is certainly the definition of the gate of the active device. To operate up to 77 GHz, the gate length needs to be 0.25μm maximum with a multiplied approach and 0.1μm with a fundamental solution. The definition of the gate is realized by exposing the resist protecting the substrate with ultra-violet (UV) light, or electron beams (EB). Today, in the manufacturing of Silicon chips, 0.5μm gates using optical steppers are common. This machine is certainly the best manufacturing tool available for the job. It gives excellent definition and repeatability and has a throughput of 50 wafers/hour. Assuming 4 inch wafers (5000 mm^2 available area/wafer), a production requirement of 2M radars/year, a total chip set area of $8mm^2$, an overall yield of 20%, 300 days/year, and 24 hours/day, we have : # wafers/year = 2M X 8 / 0.20 / 5000 = 16000/year = 53/day =2.2/hour. Therefore, with one optical stepper, the foundry has plenty of capacity available in the gate process area. The cost of an optical stepper is about $3M and is comparable to the cost of an E-beam. In the Silicon and GaAs industry, 0.5μm steppers are common, and work is underway to go to 0.25μm. That is as far as an optical stepper will go. If 0.1μm lines are required there is only one choice: the E-beam. X-ray steppers could become available in 5 years, but it is doubtful. An E-beam can process only 1 wafer/hr at best. In addition, 0.1μm gates are not easy to produce. Even though the capacity can be increased to 3-4 wafers/hour, 0.1μm lines will represent the yield limiting step in the overall process.

0.25mm DEVICES : GaAs POWER MESFETs AND PHEMTs

Due to the reduced electron mobility, compared to PHEMTs, 0.25μm GaAs Power MESFETs cannot efficiently operate beyond 40 GHz. Therefore, for operations at 77 GHz, this device requires a X2 or higher order multiplied solution. Due to the multiplication loss, the efficiency is seriously degraded to around 1%. The phase noise does not meet the requirements of an FMCW radar. At 38 GHz, a 0.25μm MESFET oscillator will not achieve better than 70 dBC/Hz 100 KHz from the carrier and the X2 multiplication will degrade the phase noise by at least 6dB. Improvements are possible with external dielectric resonators, but, at 38 GHz, their frequency centering and positioning are not easily reproducable. In terms of availability, a few foundries [1] have already developed a chip set based on this technology but several other foundries have the know-how. The reliability of the device has to be considered good. The entire source, including the VCO, amplifiers and multiplier can be integrated in a single chip of around $5mm^2$. In quantities of 100,000/year, this technology will cost around $4/$mm^2$ and therefore a cost of $20 is achievable. To improve the efficiency of the previous solution, 0.25μm PHEMTs can be used. Due to their higher electron mobility, these devices, with the same gate length, exhibit higher gain and power efficiency. The same output power of (17dBm) can now be produced with an efficiency of 2% or better. The phase noise is as poor as that of a MESFET. The cost is comparable to MESFETs as the size of the chip can be reduced but the cost/mm^2 will increase. In any case, an overall cost of $20 is achievable. Reliability, because of improved efficiency, is better.

0.1 μm PHEMTs AND 1 μm HBTs

A fundamental oscillator/buffer at 77 GHz is only possible if the gate length is reduced to 0.1μm. The power efficiency is now improved to better than 6%. Therefore the reliability is enhanced because of lower power dissipation. The phase noise will not be better than 60 dBC/Hz at 100 KHz. Even though the cost/mm^2 is higher, the reduced size of the chip could meet a $20 target. However their production maturity is still years away. The only monolithic device capable of achieving phase noise characteristics similar to Gunn diodes is the Heterojunction Bipolar Transistor (HBT). Its phase noise behavior, due to the low 1/f cut-off frequency is excellent especially for Silicon (SiGe) based devices. 1μm HBTs could perform well as oscillators at 38 GHz, but these devices are not available in production today or any time soon.

FINAL COMPARISON AND CONCLUSIONS

GaAs diodes meet our cost target and phase noise requirements, but are short in power. InP diodes supply the power but are too expensive. If the phase noise is not critical, a 0.25μm monolithic solution meets the requirements. To improve the phase noise, a monolithic solution could use an external resonator. PHEMT technology is recommended because of higher efficiency. 0.1μm PHEMTs, have the advantage of functioning in the fundamental mode at 77 GHz. Even though the overall transmitter chip area will be smaller, the overall cost will not necessarily be lower because of reduced yields compared to 0.25μm PHEMTs. Finally HBTs have a tremendous potential because of their high efficiency and phase noise behavior, but their process maturity is still years away.

REFERENCES

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