A Low Cost K-band Doppler Radar Sensor for Traffic Control Applications

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***Abstract* — A low-cost short-range K-band Doppler radar sensor for traffic control applications has been developed. The compact sensor, including a waveguide front-end module and a planar patch antenna, weighs only 0.1 lb. The module incorporates a Gunn oscillator, a mixer and a simple coupling/duplex configuration; the antenna is realized on a 0.031" thick Rogers 4003 laminate to allow its stand alone operation. The antenna is fed by the module through a unique dual waveguide-to-microstrip transition which is also integrated in the patch antenna design. It is anticipated that this simple low-cost sensor has a more than 100 meters detection range.**

***Index Terms* — Doppler, radar, sensor, patch antenna, traffic control, front-end module.**

I. INTRODUCTION

With increasing traffic density on today's roads, there is a rapidly growing interest in intelligent transportation systems (ITS). The mm-wave CW Doppler radar sensors have been active in various industry applications such as automotive speed measurement & law-enforcement, liquid flow control, hospital patient surveillance and intruder detection in security system for decades [1][2][3], and played a particularly important role in ITS. As ITS applications intend to serve a mass–market, cost of the sensor systems should be as low as possible.

Though mm-wave technology has progressed quickly enough to the point that novel techniques and approaches such as mm-wave monolithic integrated circuits (MMIC), flip-chip planar circuits and system-on-chip (SoC) have been making the mm-wave sensors massively producible, cost reduction for those high performance sensors is still facing many challenges and remains a serious problem.

However, for those applications such as traffic monitoring, traffic data collection, and speed display trailers installed often in crowded traffic gateways and in construction/school zones, the required sensor detection range is typically only 100 meters or less. For these short range, typically high volume applications, the driving factors are compact size and simple functionality rather than high performance such as sensitivity. For this reason, cost reduction is possible. One such radar sensor that meets these requirements is presented here.

II. DOPPLER SENSORS FOR VEHICLE SPEED MEASUREMENT

All existing traffic radars to be used for speed monitoring and enforcement are based on a simple CW Doppler technology. This means that the radar continuously emits a radio wave (frequency f) which is partly reflected by the passing vehicle with a frequency shift Δf in compliance the Doppler effect, which is proportional to the speed v of the vehicle ($\Delta f = 2f\,v/c$, c: velocity of light). As illustrated in Fig. 1.

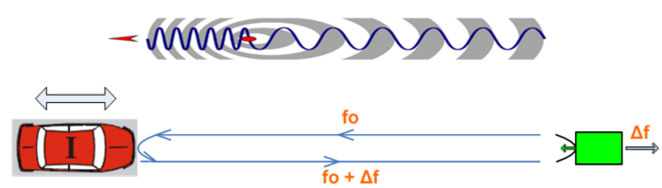

Fig. 1. Speed measurement principle based on Doppler effect.

Radars determine v by measuring the frequency shift Δf, via a frequency down-converter in a homodyne transceiver configuration followed typically by a signal conditioning circuitry which amplifies, filters and processes the signal. Fig. 2 shows a block diagram of a typical Doppler radar set.

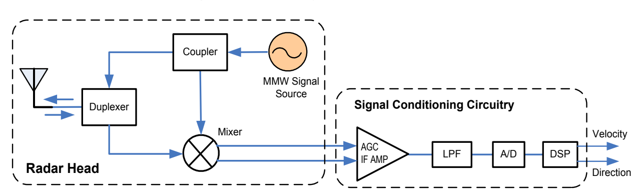

Fig. 2. A typical homodyne Doppler radar set.

A dual channel I/Q mixer should be used if vehicle direction information is also necessary. By applying a Voltage Controlled Oscillator (VCO) as the mm-wave signal source, an FMCW radar can be configured to obtain the vehicles' distance information. To extend radar detection range, one can insert a power amplifier (PA) in the transmit path and a low noise amplifier (LNA) in front of the mixer in the receive path respectively. What we present here is the development of the sensor head.

III. LOW COST K-BAND SENSOR CONCEPT AND DESIGN

The low cost K-band sensor was initiated by voice-of-customer and is to be applied in the low end traffic radar market in the unlicensed 24.125 GHz ISM band. The targeted radar operation range is 50-100 meters with an emitting power of within 5 dBm (EIRP within 26 dBm) and an angular coverage of 12 degrees in both azimuth and elevation.

To reduce the unit cost, the homodyne transceiver front-end was configured into a single waveguide module and a microstrip planar type patch array antenna was chosen for miniaturization purposes as well. The final radar head is a simple put-together of the front-end module and the planar antenna through an aperture-coupled feed structure.

A. Sensor Front-end Module

The waveguide module integrates a Gunn oscillator and a Schottky mixer into a single metal block. Fig. 3 illustrates a top view of the front-end module.

Fig. 3. Sensor front-end module illustration.

A Gunn oscillator is adopted in this sensor design as the mm-wave signal source due to its superior spectrum quality as well as its low cost and ease of operation. The 24.125 GHz mm-wave energy generated by a Gunn diode which is mounted in a high-Q oscillation cavity passes through an opening iris and is then focused into a beam which transmits out by a planar antenna. The reflected signal from a moving object is detected by a Schottky barrier diode which is mounted in the WR-42 output waveguide off the center. It mixes with a small portion of the transmitting energy as LO there and the resulting differential Doppler signal is available at the "IF Out" terminal. The size of the rectangular iris can be adjusted to control the sensor's emitting power level.

In this transceiver module there is no duplexer in place for system simplicity. This configuration typically results in a serious Tx/Rx leakage due to the lack of isolation between them. Fortunately, however, for this homodyne transceiver, which is focused on the detection of Doppler frequency shift, the leakage is not big enough to saturate and block the mixer diode and its impact to performance can be minimized, by using AC coupling at its IF output to cut away the DC mixing result.

To further limit the Tx leakage to the receiver, the mixer diode needs be placed away from the waveguide center, resulting in a receiver sensitivity sacrifice. Therefore, a trade-off balancing effort is always in play and the sensor's usage is limited for long range applications. Fig. 4 shows a real K-band sensor module. Putting another Schottky diode on the other side of the waveguide with certain space in longitudinal direction can simply make the module dual channel with I/Q output.

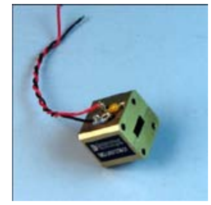

Fig. 4. A photo of sensor front-end module.

B. Planar Patch Antenna

A very low cost patch antenna was designed with the target of 20 dB gain and 15 dB worst case side lobes. To keep the cost low, it was decided to make the antenna printed on Rogers 4003 despite the high dielectric constant and to use a 0.031 inch thick material so that no back plate would be required – the PCB is screwed directly to the sensor front-end module compressed between the waveguide backshort and the module.

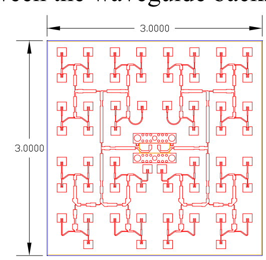

Fig. 5. The designed 24.15 GHz patch antenna.

To achieve the gain while maintaining the minimum beamwidth, an 8x8 array was designed. Fig. 5 shows the circuit board pattern without the waveguide backshort. Because vertical polarization was desired with a centered waveguide-to-microstrip transition, the transition was configured to include the first H plane splitter, also shown in Fig. 5. With a ¾ lambda spacing of 0.37", the 64 element array fit on a 3 inch by 3 inch PCB. The feed network was designed with a 10 dB taper in both planes to achieve the 15 dB side lobes with some margin. To allow room for the waveguide transition, two patches were removed and two shifted down.

The dual waveguide-to-microstrip transition was designed in HFSS@Ansoft. The half model with a symmetry plane and the modeled return loss results are shown in Fig. 6.

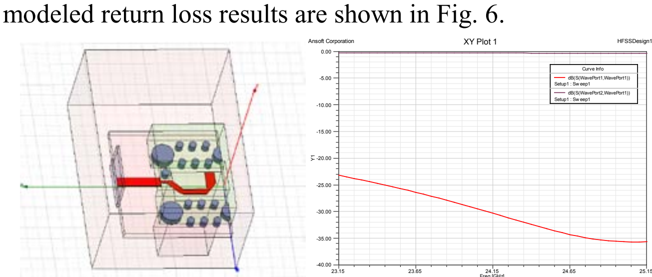

Fig. 6. The dual waveguide-to-microstrip transition model in HFSS and simulated return loss.

The array itself was also designed in HFSS. Due to the thickness of the circuit board, and the high dielectric constant of the Rogers 4003, the patches allow too many higher order modes, and end launch a significant amount of energy into the surface modes. Due to the surface modes and very high mutual coupling, the specified side lobes were unachievable even with substantial amounts of trial on feed phase and amplitude distributions. HFSS did predict that the gain was achievable, and since the critical H-plane side lobe levels were predicted to be in spec, the antenna was built. Since the antenna is an imbedded component, the return loss from neither the WG-to-MSTP transition nor the antenna could be measured. The antenna pattern was determined by measuring EIRP versus angle and normalizing. The predicted and measured gain results are shown in Fig. 7

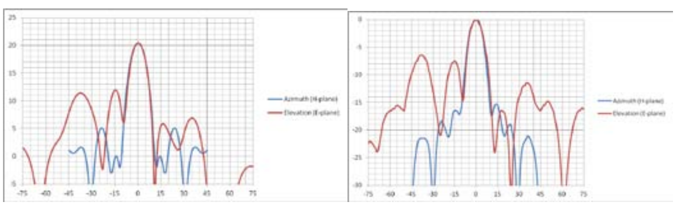

Fig. 7. Antenna gain simulation (left) and measurement results.

The measured versus modeled results are similar, but less accurate than would normally be achieved with a higher cost, higher performance material such as Rogers 5880. The measured gain came in at 17.4 dBi versus calculated 20.4 dBi.

Although some analysis was done on the implementation of the circuit traces, no major discrepancy was discovered that could account for the missing 3 dB of gain. Very likely the loss tangent is higher than used in the model which was not measured at 24 GHz.

To meet the higher gain, an 8x8 array needs to be built on 0.01 inch thick Rogers 5880 but requires a back plate. To remain low cost with 0.031 inch thick material for stand alone operation, improvements can likely be made using low loss and low dielectric constant board material to suppress the higher order modes.

Fortunately, the current design antenna with measured 17.4 dBi gain adequately serves most low-end traffic applications and the design goals of this integrated assembly.

C. Sensor Assembly

The final radar sensor head is a simple put-together of the developed waveguide front-end module and the patch antenna board.

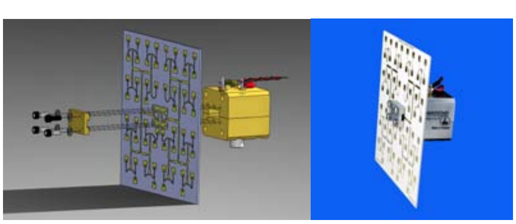

Fig. 8. Sensor head assembly and photo.

As shown in Fig. 8, the Rogers 4003 patch antenna is mounted to the front-end module via 4 crews and two dowel pins, without the need of a back plate, by aligning its aperture on the feeding back to the WR-42 opening of the module.

The frequency of the sensor is tunable through a tuning rod and the Doppler IF signal outputs through a feed-thru pin on the module top. The entire sensor weighs only 0.1 lb.

IV. DETECTION RANGE ESTIMATION

With the achieved spec parameters of the front-end module and the patch antenna, and based on the well-known radar equation [4] and the thermal noise based receiver Minimum Detectable Signal (MDS) calculation, the K-band low-cost sensor's detection range could be estimated with our Radar Range Calculator, in table I.

TABLE I. SENSOR RANGE ESTIMATION

Radar Range Caculator						
f: Frequency	24.15	GHz				
Pt: Transmit Power	5	dBm		Radar Sensitivity (MDS)	-116.75	dBm
Gt: TX Antenna Gain	17.4	dBi	→			
Gr: RX Antenna Gain	17.4	dBi		Radar Operation Range	136.94	m
NF: RX Noise Figure	8	dB				
B: RX Noise Band Width	100	KHz				
RCS: Target Radar Cross Sction	1	m^2				

**No atmospheric attenuation and weather condition considered

Assuming a typical 8 dB Rx noise figure, 100 KHz Rx noise bandwidth and one square meter target Radar Cross Section (RCS), the sensor's detection range was estimated to be about 137 meters, which is still well within or even exceeds our design goal. This sensor is currently provided to customers for field testing, with a commercial market price of around 100 USD.

V. CONCLUSION

A compact, low-cost K-band Doppler sensor head suitable for low end mm-wave traffic information collection and speed display trailer applications has been described. Though the realized stand-alone PCB antenna gain is 3 dB lower than expected, the anticipated sensor detection range is still within the design and application goal. The design of modularized front-end and single PCB antenna makes the sensor a good fit for the high-volume, low-cost production.

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