A 76-77GHz PULSED-DOPPLER RADAR MODULE FOR AUTONOMOUS CRUISE CONTROL APPLICATIONS

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ABSTRACT

A single-substrate radar transceiver module suitable for 76-77GHz pulsed-Doppler applications has been developed. The packaged transceiver, including three waveguide ports and IF output, measures 20 x 22 x 8mm. The circuit is realized using discrete GaAs/AlGaAs pHEMTs, GaAs Schottky diodes and varactor diodes, as well as GaAs PIN and PHEMT MMICs mounted on a low-cost 127μm thick glass substrate.

INTRODUCTION

The field of radar for automotive applications and other mm-wave sensors is attracting great interest and investment [1]. The focus to date has been hardware demonstrations that fulfill the required functionality [2], [3]. Currently available Autonomous Cruise Control (ACC) radar systems are unlikely to meet the projected cost profile increased consumer take-up requires.

With projected demands of millions of units a year, the problem of high-volume, low-cost, high-yield manufacturing and testing of these systems has not been adequately addressed beyond the development of MMIC building blocks [4-7], although recognition of the issue is increasing [8]. Even with these MMICs, the problem of integration with a circuit medium, packaging, and providing other mechanical and electrical interfaces remains a technically challenging and potentially costly issue [9]. A successful resolution of this issue requires a design approach that considers not only the electrical functionality, but also the means of integration and packaging and, perhaps more importantly, the compatibility with automated high-volume manufacturing techniques [10], [11].

The radar transceiver described in this paper was designed using several novel techniques to address and resolve these issues. The module principally consists of low-cost, high-yield discrete devices that are mounted using conventional and proven assembly techniques onto a glass substrate. The novel packaging technique allows for rapid interchangeability of mm-wave modules within each radar system, facilitating test. The module presented in this paper, along with all of the separately tested individual components, met specification on the first attempt.

TRANSCEIVER COMPONENTS AND ARCHITECTURE

The radar transceiver is realised by mounting discrete active devices and MMICs onto a glass substrate. Discrete devices are used in preference to MMICs wherever possible for two reasons; firstly, the yield and relative cost/unit area of a discrete device is significantly lower than that of a MMIC. Secondly, the designer is not restricted to the limited number of device types typically available in a given MMIC process. Semiconductor devices are mounted by flip-chip attach for the varactor and Schottky diodes, and using normal and compensated wire-bond interconnects for the PHEMTs and MMICs.

The glass substrate is realized using M/A-COMs proprietary passive GMIC process [12], [13].

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Silicon and glass are combined to create a low-cost circuit medium that has attractive properties for millimeter-wave design. In this instance, the substrate contains low-loss transmission lines and biasing networks as well as providing a low-loss microstrip to waveguide interface by means of a special mode transducer and launch network. Microstrip, coplanar waveguide, lumped and distributed circuit elements and isolating RF ground shields can and have been utilized wherever appropriate for the circuit design. The components can be placed either flip-chip or upright using standard automated high-volume manufacturing equipment. All bondwire interconnects are designed to be implemented with standard 25μm diameter ball-bonds. A photograph of the complete transceiver module is shown in Figure 1.

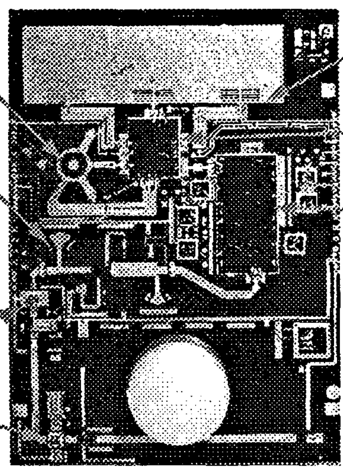

Figure 1 – The complete 76-77GHz transceiver module as realized using a glass (GMIC) substrate

The ACC system is a switched three-beam pulse-Doppler radar operating at 76-77GHz. Figure 2 illustrates the module block diagram employed. The output from a voltage controlled oscillator (VCO) at 19GHz, thermally stabilized by a dielectric puck, is amplified and multiplied to 38GHz. The VCO, amplifier and multiplier are based on upright bonded discrete PHEMTs and flip-chip mounted varactor diodes. The 38GHz signal is then further multiplied and amplified to provide an output signal at 76GHz.

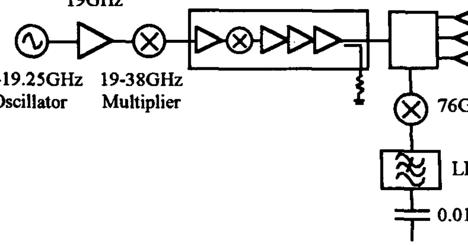

Figure 2 – Circuit block diagram of the 76GHz transceiver module

An alternative configuration to that described that further reduces the area of active semiconductor material required, and thus the cost, is to replace the 38-76GHz MMIC by a 38GHz driver-amplifier and a second passive multiplier. The passive varactor-diode multiplier circuit needs careful design for thermal management of the power dissipated in the varactor junction.

When the module is in transmit mode (TX), the 76GHz signal is directed via the PIN switch MMIC to one of three antenna feeds providing azimuth object detection. This switch is a modified version of the reflective GaAs PIN switch described by Putnam *et al*, that is capable of being RF tested with a six-port test system for providing known good die [14]. In receive mode (RX), the 19GHz VCO is tuned to an appropriate IF offset and the 76GHz + IF is switched to the LO arm of the mixer. The return signal received by the antenna is then heterodyne mixed with the LO and the IF recovered.

MODULE ASSEMBLY AND MANUFACTURING

The aggressive price targets of the consumer marketplace demands that not only should the material costs of the millimeter-wave circuitry be minimized, but that assembly should be automated, and the design be insensitive to typical manufacturing and device tolerance variation to maximize yield. Furthermore, the integration and test of the completed module should be possible without complex and expensive alignment or manual re-work procedures.

The glass substrate is mounted on a metal header that forms the package base and also the mounting surface for the three-waveguide feeds. The mm-wave interface between the transceiver module and the waveguide feeds is a tapered waveguide channel fed from a patent pending microstrip to waveguide mode transition on the front-side of the glass substrate. The metal header is compatible with standard high volume metal-injection-molding (MIM) technology. The glass circuit can be attached to the metal header using pick-and-place technology. The transition between the planar circuit on the front-side of the substrate and the waveguide-feeds in the base of the package is capable of misalignment by up to 200μm providing a robust design for variation in placement in assembly.

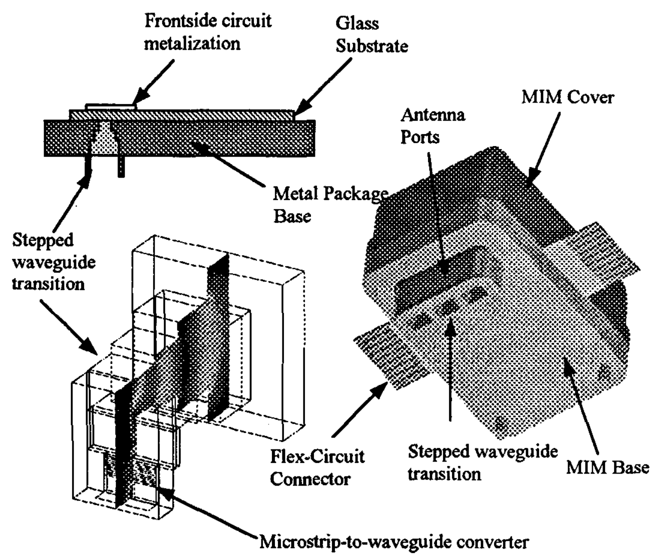

Figure 3 – Waveguide transition and package detail showing the concept of the 'drop-in' millimeter-wave module

The glass substrate mounted on the MIM base contains all of the millimeter-wave circuitry. An MIM cover is added to provide a self-contained drop-in millimeter-wave module. All electrical interfaces between the module and the control and DSP circuits are maintained via the flex-cable. The module is mounted on the radar control board using a spring-clip attachment that allows for movement due to thermal effects of the mechanical interface. A common RF ground is established for the antenna by an interference-fit between the antenna ports and a corresponding recess on the antenna ground plane. The millimeter-wave module is easily integrated and removed from the radar module allowing for ease of testing and modular assembly.

The active devices and the dielectric puck may be mounted using conventional surface-mount pick-and-place technology. The discrete PHEMT devices used in the oscillator and amplifier are mounted upright and wire-bonded. The varactor diodes in the oscillator and frequency multipliers, and the Schottky diodes in the mixer are mounted using conventional flip-chip attach with a conductive silver loaded epoxy. Care must be taken in non-hermetic enclosures to ensure that the bias across the devices does not encourage silver-migration from the epoxy that compromises device reliability.

Although flip-chip attachment of discrete devices is a relatively trivial exercise, concerns with ground-plane coupling causing hybrid modes plus thermal management of heat dissipation makes the process more problematic for MMICs. In addition, the mismatch between the thermal coefficient of expansion of the MMIC and the substrate can require the use of an underfill material that can complicate circuit design. The MMIC circuits were thus mounted in the conventional upright position and connected using wire-bonds.

The use of compensated wire-bond interconnects that have an insertion loss of < 0.2dB at 77GHz for bond-wires of length between 380μm-480um makes this compatible with the typical tolerance from an automated wire-bond machine [15].

MODULE INTEGRATION AND CIRCUIT RESULTS

The measured results of each of the circuits shown in Figure 2 are summarized in Table 1. The module level results were obtained by mounting the transceiver module with a quasi-optical antenna from a commercially available ACC system. Figure 6 is an azimuth plot of the switched 3-beam antenna pattern for the transceiver module in transmit-mode. Each of the three beams provides approximately 3° of azimuth coverage, whilst sidelobe levels are typically –16dB.

Description	Measured Performance
19GHz DRO and Amplifier	- Δf_0 120MHz for 8V tune voltage - +14dBm ± 0.75dB (-40°C to +85°C) - Frequency Drift ~ 12 MHz - Switching speed < 5nS (10% DC to 90% RF) - SSB Phase-Noise ~ -92dBc/Hz@100kHz
19-38GHz Doubler	- 8dB conversion loss for +10dBm to +16dBm input power level (2.2V bias) - practically constant conversion loss over temperature - >15dB fundamental frequency rejection
76GHz Mixer Ref. [16]	- <6dB conversion loss with 90% yield for +8dBm to +16dBm LO drive; IF = 180MHz
PIN MMIC	- Insertion loss (Tx to antenna) 3±0.5dB - Insertion loss (antenna to Rx) 2±0.5dB - Isolation (2-ports) > 23dB; 32dB typical
38-76GHz Doubler	- 12dB conversion loss for +18dBm to +23dBm input power level - practically constant conversion loss over temperature

Table 1 – Measured performance of the components used in the millimeter-wave module

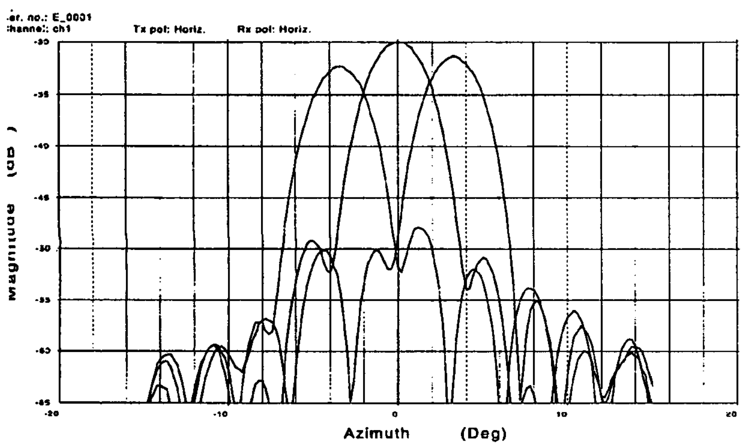

Figure 4– Azimuth beam pattern of the radar module in each of the three transmit beam states

CONCLUSIONS

A compact, complete transceiver module suitable for mm-wave (76GHz) vehicular radar applications has been described. All of the materials and assembly techniques used in the design are compatible with the low-cost objectives that the commercial mm-wave industry requires. The design philosophy behind this module represents a significant step forward in the ability to generate low-cost and high volume, consumer millimeter-wave products.

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