Integral Microwave Circulators for Multi-Chip Module (MCM) Applications

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ABSTRACT

The integration of passive components into multi-chip modules (MCM) provides a path for reducing the size and cost of microwave modules while minimizing interconnect parasitics. One passive component which is frequently used in transmit/receive modules of active phased array systems is the circulator. In this paper, an S-band Y-junction circulator was integrated into a MCM using High Density Interconnect (HDI) technology. HDI is a chips first approach where ICs are placed in cavities formed in a ceramic or plastic substrate. An interconnect layer is formed above the ICs, vias are used to make contact with the pads of the IC and Ti/Cu/Ti metalization is used to form the multi-layer interconnect. The S-band circulator fabricated in HDI displayed excellent electrical characteristics while minimizing losses incurred when a circulator is interconnected to a microwave module.

I. INTRODUCTION

Circulators are one of the most widely used microwave control components which utilize magnetic materials. A circulator is defined as a device which couples energy from one port to the adjacent port while isolating the third port. One high volume application where circulators are commonly used is active phased array antennas. These antennas usually consist of thousands of Transmit/Receive (T/R) modules with each module containing at least one circulator. In order to minimize size, cost and weight of phased array antennas, the T/R modules are usually fabricated as multi-chip modules (MCMs). MCMs consist of bare ICs and passive devices interconnected into one package. The ability to integrate passive components into an MCM is one path to further reduce the size and cost of the total package. In this paper, we will discuss the fabrication of an integral circulator in a "chips first" MCM technology known as High Density Interconnect (HDI). In this technology, the circulator is formed along with the MCM interconnect. The implementation of an integral circulator in the GE HDI technology is shown in Fig. 1.

The demonstration circulator which was chosen for integration into the HDI packaging technology is a narrow band application with a frequency range from 2.7 GHz to 2.9 GHz. The specifications for the electrical characteristics are as follows: (1) insertion loss < -0.5 dB, (2) return loss < -15 dB, and (3) isolation < -15 dB.

II. THEORY AND DESIGN

The design of stripline and microstrip line Y-junction circulators is generally based on the works of Bosma [3], Fay and Comstock [4], and Wu and Rosenbaum [5]. There are a number of physical variables that have to be determined in order to design the circulator. They are : (1) the radius of the metalized ferrite disk, (2) the thickness of the ferrite puck and (3) the width of the port arms. The necessary materials parameters are: (1) the dielectric constant of the ferrite puck and surrounding dielectric and, (2) the saturation magnetization of the ferrite ($4pM_S$).

For our circulator which should operate from 2.7 GHz to 2.9 GHz, we chose a ferrite with a 4pMs of 670 Oe which corresponds to a ferrite anisotropic splitting ratio of 0.66 at the center frequency of operation (2.8 GHz). The respective ferrite anisotropic splitting ratio for the two endpoints of the frequency range (2.7 GHz and 2.9 GHz) are 0.69 and 0.64. This is well within the range of 0.51 to 1.0 stated by Wu and Rosenbaum as the operating range of their circulator design.

The ferrite disk radius (R) for our circulator was calculated from the following Wu and Rosenbaum equation [5]

$$SR \approx 1.20 \qquad (4)$$

where $S = (\omega/c) * (m_{eff} * \varepsilon_f)^{1/2}$, $m_{eff} = (\mu^2 - k^2)/\mu$, and ε_f is the relative dielectric constant of ferrite. Substituting Equations (2) and (3) into Eq. (4) and solving for the ferrite disk radius, we obtained a value of 7.49 mm. Correspondingly the port angle of 0.5 radians results in a port width of 0.336 mm.

Using the port width, the dielectric constant of the ferrite and the thickness of the ferrite, we can compute the input impedance of the circulator normalized to the characteristic impedance of the microstrip line at the edge of the junction. The formula for the circulator input impedance operating in the below resonance mode was obtained from Wu and Rosenbaum [5]. Using this formula for our case, the magnitude of the normalized circulator impedance was calculated and Fig. 2 shows a plot of the normalized impedance magnitude as a function of frequency.

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For the frequency range of 2.7 GHz to 2.9 GHz, the normalized circulator impedance magnitude varied approximately from 1.07 to 1.09. To compute the actual circulator impedance, the characteristic impedance of the microstrip line at the edge of the junction was calculated. Using a ferrite dielectric constant of 13.90, a ferrite thickness of 0.635 mm, and a Cu metal thickness of 4 μm, a value of 7.4 Ω was calculated for the microstrip line at 2.8 GHz. Multiplying the normalized circulator impedance magnitude of Fig. 2 with the characteristic impedance of the microstrip line at the edge of the junction, one can obtain the actual circulator impedance magnitude. For the frequency range of 2.7 GHz to 2.9 GHz, the actual circulator impedance magnitude be approximately 8 Ω. The impedance at the end of 2.2 mm long port arms of the circulator will be approximately 9.6 Ω. In order to match the circulator impedance to 50 Ω from the end of each port arm, an impedance transformer is required. A microstrip quarter-wave transformer was chosen and fabricated on the HDI interconnect. The top view of this integral circulator is shown in Fig. 3. In this figure, we observe a port arm length of approximately 2.2 mm on the ferrite followed by an HDI quarter-wave transformer.

III. EXPERIMENT

The integral circulator was fabricated using the HDI packaging technology. The fabrication process began with the patterning and sawing of the ferrite followed by the placement and connection of the ferrite in the HDI package to form an integral circulator. The initial steps consisted of metalizing a 3" x 3" sheet of ferrite with Ti (1000Å) / Cu (4 μm) / Ti (1000Å) on the front side and 1000 Å(TiW) / Au (4 μm) on the back side followed by patterning the entire ferrite sheet with the microstrip circulator design. The microstrip circulator design pattern on the ferrite consisted of the circulator disk with three port arm extensions. The quarter-wave transformer for each of these port arms was fabricated on the HDI interconnect. An array of circulators were patterned on this ferrite sheet. After this step, the ferrite sheet was sawed to form individual circulator elements.

In the HDI MCM package, each active and passive component is die-attached into a milled cavity in a ceramic or metal substrate. When ceramics are used, the milled substrate is metalized with 1000 Å TiW/ 4 μm Au prior to die attach to form the ground plane. The ground plane is non-planar and continuous from the bottom of milled cavities to the top surface of the ceramic. The circulator elements, in this case, were die-attached into metalized milled cavities in an Alumina substrate. The 96% Alumina substrate was 1.27 mm thick and the milled cavities had a depth of approximately 0.66 mm. A conductive silver filled epoxy was used for the die attach.

Following die-attach of the circulator element, the HDI interconnect is formed above the components. The HDI interconnect consists of layers of adhesive and Kapton E® laminated in successive steps with laser drilled vias to interconnect the device to the HDI interconnect. The adhesive thicknesses range from 11 to 13 μm and the dielectric film thicknesses range from 22 to 24 μm. An Ar^{+} laser at 351 nm is used to from the vias and pattern the interconnect. In this case, three Kapton E® layers were laminated to from the interconnect and the microstrip quarter-wave transformer was patterned on the top layer. A stack of laser drilled vias were used to connect the circulator element to the quarter-wave transformers. Since the ground plane is located at the top surface of the ceramic, the total dielectric thickness was approximately 102 μm.

A thin (100 mils) ceramic magnet was used for the biasing of the circulator. The magnet was placed on the top HDI interconnect layer and aligned to ferrite with the use of alignment marks patterned on the interconnect. Permanent attach of the magnet can be achieved with the use of an epoxy.

IV. RESULTS

A HP 8510B network analyzer with an Alessi REL-4300 probe station were used to determine the S parameters for the integral circulator. Ground - Signal - Ground (GSG) probes were used for the measurements. A standard two port SOLT calibration was performed prior to measurements. Since the circulator is a three port device, the third port was uncalibrated and connected to a 50 Ω load. The three parameters measured for the circulator were insertion loss, return loss, and isolation. The S parameters were measured from 2.0 GHz to 4.0 GHz. Fig. 4 shows the three measured parameters for the HDI integral circulator. The insertion loss for this circulator, shown in Fig. 4(a), is -0.6 dB from 2.7 GHz to 2.9 GHz. For a broader frequency range, 2.4 GHz to 3.2 GHz, the insertion loss is less than -1.0 dB. The return loss for this circulator, shown in Fig. 4(b), is below the required -15 dB for the frequency range of 2.4 GHz to 3.2 GHz. Finally, the isolation (Fig. 4(c)) is also below the required -15 dB for a broad frequency range of 2.4 GHz to 3.2 GHz.

V. DISCUSSION

A circulator fabricated integrally in a HDI multi-chip module package technology has successfully met our electrical specifications while minimizing the losses one incurs when a circulator is interconnected to a microwave module. For this integral circulator, the quarter-wave transformers for the three ports of the circulator were fabricated on the HDI interconnect. The HDI microstrip quarter wave transformer used for the circulator had a 0.7 mm width and a length of 15.9 mm on a 102 micron thick dielectric with a 3.10 dielectric constant. This corresponds to a 24 Ω impedance for the transformer. With a return loss better than -20 dB for the 2.7 GHz to 2.9 GHz band, the input impedance at the end of the ferrite port arms is approximately 11 Ω. This is reasonably close to the value of 9.6 Ω obtained from theory.

In order to understand the losses of this integral circulator, let us calculate the losses of the ferrite circulator disk and the quarter-wave transformers. The losses of the quarter-wave transformer was calculated by first determining the current and voltage equations and then integrating the product of the current and voltage equations across the quarter-wave length to obtain the losses. The microstrip quarter-wave transformer in our case was 15.9 mm long with a width of 0.70 mm on a 102 micron thick dielectric with a 3.1 dielectric constant. The calculated losses for one quarter-wave transformer at 2.8 GHz was -0.27 dB. The losses of the ferrite circulator disk was calculated from Eq. (10c) of the Wu and Rosenbaum paper [5]. For our case, the ferrite circulator disk losses at 2.8 GHz was approximately -0.08 dB. The total losses for the circulator at the center frequency of 2.8 GHz is therefore -0.62 dB. In comparison with the experimental results, we observe that at 2.8 GHz, the insertion loss from Fig. 4(a) is -0.6 dB. The computed loss values are very close to the experimental results and they indicate that the losses of this integral circulator are dominated by the quarter-wave transformers. We can also infer from this comparison that losses due to HDI package parasitics are negligible and do not affect the performance of the circulator at these frequencies.

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The power handling capability of the integral circulator is strongly dependent on the thermal properties of the GE HDI MCM package. Specifically, the two thermal issues for the integral circulator are: (1) maintaining the ferrite below the Curie temperature and (2) not exceeding the power handling capability of the microstrip feed lines. Utilizing the insertion loss data of the ferrite from the 2.8 GHz circulator, the thermal properties of the materials used in the HDI MCM package and a 2-D thermal analysis program, the thermal resistance from the surface of the ferrite to the heat sink was calculated to be approximately 1.14°C/W. A similar analysis was performed for the microstrip feedlines to the ferrite which is part of the HDI MCM interconnect. In this case, heat generated from the microstrip lines spreads through the dielectric interconnect layers, through the Alumina substrate to the heat sink. The thermal resistance from the quarter-wave transformer to the heat sink is approximately 60.1 °C/W. Comparing the thermal resistance of the ferrite to the microstrip feed lines and noting that most of the power in the integral circulator is dissipated in the microstrip feed lines, we observe that the limiting factor for thermal performance of an integral circulator fabricated in a GE HDI MCM package is the microstrip feed lines. The maximum temperature withstand of the microstrip feed line is determined by the temperature stability of the adhesives used to form the multi-layer interconnect. The upper layer adhesive, siloxane polyimide / epoxy, can withstand temperatures of 125°C in continuous operation. The maximum temperature difference between the microstrip feed line and the heat sink is the heat sink temperature subtracted from 125°C. This temperature difference will determine the power handling capability of the microstrip feed line and the circulator. For example, if the heat sink temperature is set at 25°C, the maximum power dissipation for the microstrip feed lines (one quarter wave transformer) in this study is approximately 1.6W. Using the calculated loss of one quarter-wave transformer as approximately -0.27 dB and assuming a maximum power dissipation of 1.6W, the integral circulator can handle up to 25W in continuous operation. As the temperature of the heat sink is lowered, the integral circulator can operate at higher power levels.

VI. CONCLUSION

An integral S band circulator was fabricated using an MCM packaging technology called High Density Interconnect (HDI). This circulator exhibited excellent electrical characteristics while minimizing the losses one incurs when a circulator is interconnected to a microwave module. In addition, the low thermal resistance of the MCM package allows for high power operation of the circulator. This HDI MCM technology allows for the integration of the passive integral components, such as a circulator, with active devices such as MMICs to form compact microwave systems such as T/R modules for phased array radars. For the future, integration of passive components in packages will provide a path for size and cost reduction of microwave modules.

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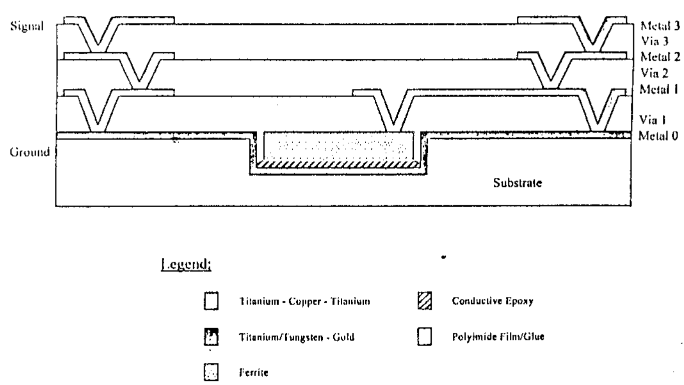

Figure 1. Integral Circulator Cross Section

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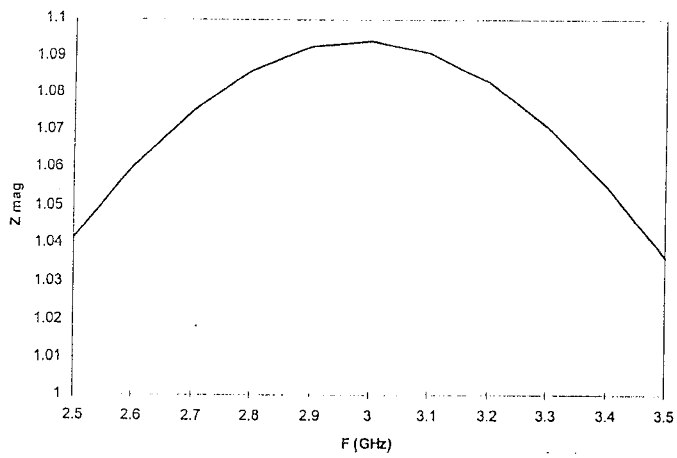

Figure 2. Theoretical normalized impedance magnitude vs. frequency for the integral circulator

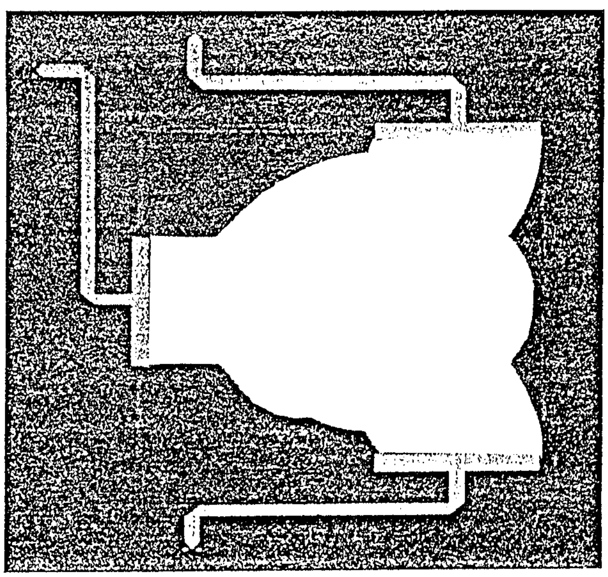

Figure 3. Top view of integral circulator

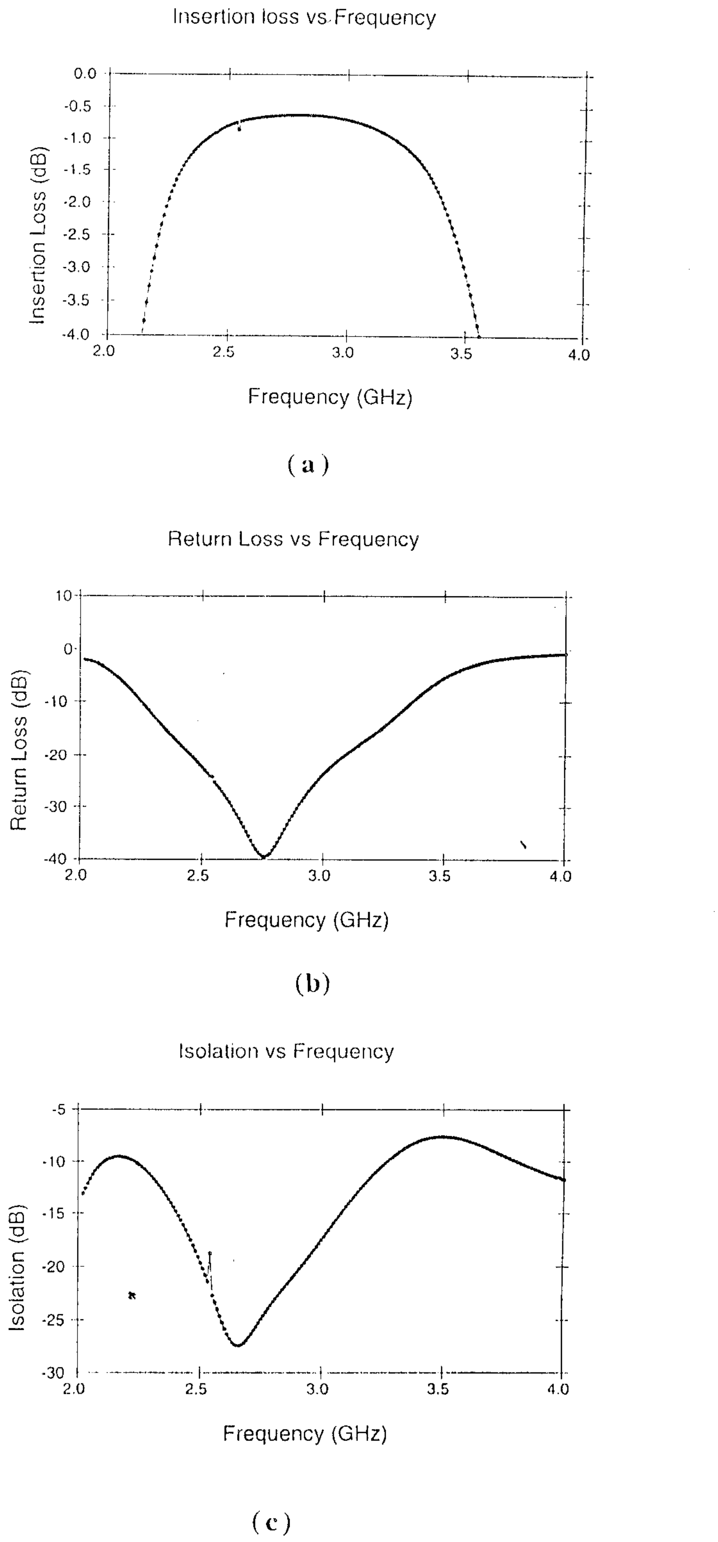

Figure 4. Electrical characteristics of the HDI integral circulator (a) insertion loss, (b) return loss, and (c) isolation.

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