Novel Module Including a Waveguide for 40 GHz High-gain Amplifier Applications

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Abstract— In this work, a 40 dB high-gain amplifier module has been presented for millimeter wave applications. Two amplifiers are integrated into the single module case by inserting a WR22 waveguide between them in the module case, in order to suppress oscillation. The high-gain amplifier module consists of two amplifiers and four WR22-to-microstrip line transitions which were fabricated on 5 mil thick RT5880 substrate. The transition loss of −0.44 dB per a transition was achieved from 35 to 50 GHz. The module showed the higher gain than 39.7 dB from 38 to 41 GHz. At 38.7 GHz, the maximum gain of 44.25 dB was obtained.

1. INTRODUCTION

The frequencies from 30 to 300 GHz are so-called millimeter-wave (mm-wave) ones, because their wavelength is between 10 to 1 mm. They have been utilized for gigabit wireless communications demanding greater amount of available bandwidth. Increasing several applications such as radars [1–3], point-to-point wireless communications, radio-on-fiber (RoF) links [4], cellular wireless networks [5], etc. in mm-wave band have been observed in the last decade.

One of main issues for commercialization of mm-wave radio systems is a reproducible and cost effective packaging, aside from the active radio frequency (RF) integrated circuit (IC) technology. Active RF IC chips are assembled on a metal or dielectric substrate carrier by using wire-bonding or flip-chip [6] interconnection and finally they are encapsulated in a plastic package or metal housing. In the small-sized package volume, various materials and structures like dielectric substrate, RF ICs, their mounting cavities, waveguides, etc. are integrated. Therefore, they can make difficult issues such as unwanted substrate modes [6], cavity resonance [7], feedback, or crosstalk due to discontinuities [8, 9], especially, in the mm-wave applications.

In the previously published literatures [6–9], these phenomena have been well analyzed. In order to prevent them, several approaches such as resistivity value of the flip-chip carrier [6], resonance condition of the cavity [7], chip mounting configurations [8], and resistive coating on the lid [10] has been investigated. Many oscillation-free modules [1, 2, 6] have been implemented by reflecting these investigations and have achieved good mm-wave performance. However, in the case of the high-gain amplifier block requiring over 30 dB, radiation of signals due to discontinuities can cause stability problem from the feedback effect [8, 9], that is, the radiated signals can enter the first amplifier IC in the whole high-gain amplifier block by reflecting from around structures in the module and can be amplified. This process is repeated and the high-gain amplifier module can be oscillated in final. Therefore, in order to prevent the feedback effect, a small- or medium-gain amplifier module is cascaded [2] in series by using external waveguides (WGs) until a required gain is satisfied. In addition, attenuators are inserted between amplifiers for reducing the whole gain and doing a role as an impedance buffer. However, these conventional approaches lead to bulky and expensive mm-wave radio system.

In this paper, a 40 dB amplifier module integrating a waveguide into the metal case has been presented for 40 GHz wireless communications applications.

2. MODULE CASE FOR HIGH-GAIN AMPLIFIER MODULE

In general, two amplifier modules are connected by using a WG for high-gain block applications in order to suppress oscillation. In this work, a WG between two cavities, in which two amplifier ICs are assembled, is integrated into the metal case of the high-gain amplifier as shown in Fig. 1. In this module case, because radiated signals due to discontinuities are confined to each cavity, another amplifier IC is not affected. Therefore oscillation can be prevented. Comparing to the conventional cascade high-gain block by using external WGs, the compact and low-cost mm-wave system can be implemented. However, low-loss W/G-to-MSL transition is required because of additional two W/G-to-MSL ones. The length of the cavity and MSL is 18.0 mm. The integrated WG is 15.7 mm long. The length of the WR22 ports is 18.5 mm.

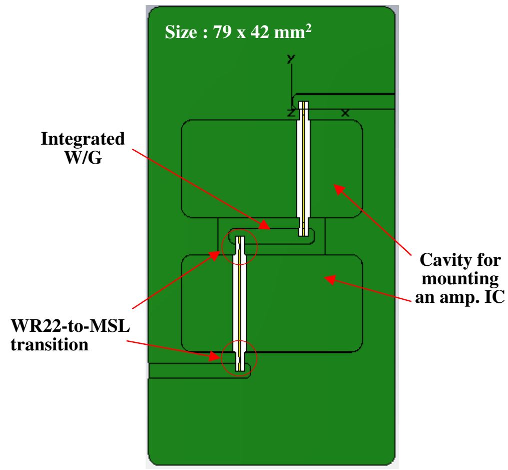


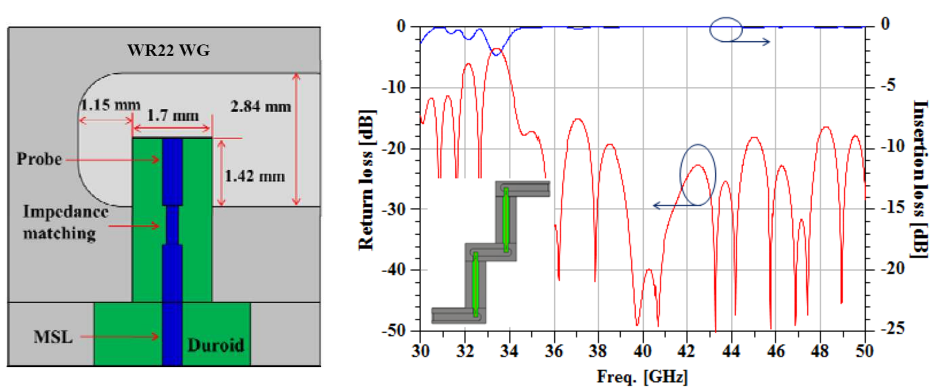
Figure 1: Proposed metal case for the high-gain amplifier module [Case size: $79 \times 42 \times 32\,\mathrm{mm}^3$].

In this work, a WR22 WG is used as input and output (IO) port. Its rectangular size is $2.84 \times 5.68\,\mathrm{mm}^2$. Two commercial amplifier ICs [11] are cascaded for high-gain remote antenna units (RAU) in the 40 GHz RoF system [4] having the gain of over 40 dB. The amplifier ICs and components for DC bias are mounted on a 5 mil thick RT5880 substrate [12]. Soldering pads for the amplifier ICs and $50\,\Omega$ microstrip lines (MSLs) as the signal line are designed on it.

3. WAVEGUIDE-TO-MSL TRANSITION

Because of the integrated WG, additional WR22-to-MSL transitions are designed. A probe-type transition is utilized for low-loss and wideband transition and two sets of the WR22-to-MSL transitions in back-to-back configuration are mounted in order to investigate their characteristics as shown in Fig. 1.

The transition was designed on the 5 mil thick RT5880 substrate and it was inserted into the WG through a longitudinal window on its longer side. The layout of the transition part is presented at the right in Fig. 2(a) and its critical dimensions were optimized for the low loss and broad bandwidth performance by using electromagnetic (EM) analysis software [13]. Fig. 2(b) presents simulated results of the designed back-to-back structured transitions mounted on the same metal case as the high-gain amplifier module in the inset of Fig. 2(b). The return loss below -10 dB is from 34.2 to 50 GH and its bandwidth is acceptable for the amplifier applications in this work.



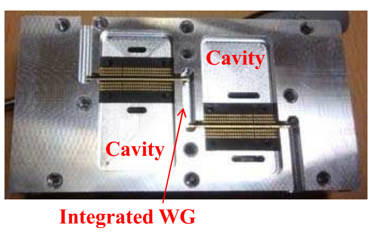
(a) (b)

Figure 2: (a) Layout of a WR22 WG-to-MSL transition and its optimized dimensions and (b) simulated results of back-to-back structured transitions integrated into the metal case [An inset: the model designed for an EM simulation].

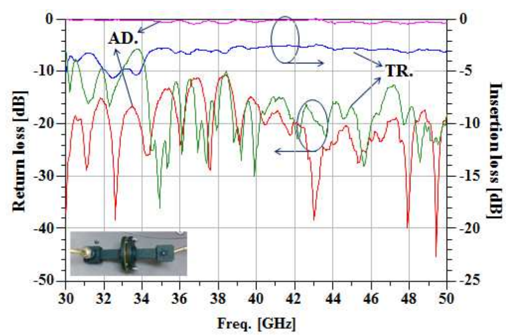
The transitions designed in the back-to-back type were fabricated by using the standard printed circuit board (PCB) process. A photograph of the fabricated ones assembled in the metal case for the amplifier module is illustrated in Fig. 3(a). For test of the transition performance, 2.4 mm-maleto-WR22 W/G adapters were used in order to interconnect a vector network analyzer (VNA, Agilent N5250A) with the transition module. Adapter losses were first checked as shown in Fig. 3(b). Its measured insertion loss (IL) is from -0.26 to -0.33 dB and the return loss (RL) is less than -10 dB at all test frequencies from 30 to 50 GHz. For the case of the transitions, the measured return loss is degraded due to the adapter and is below -10 dB from 34.1 to 50 GHz. The RL bandwidth is similar to the simulated one. The measured IL is also degraded because of loss components including the adapter, substrate (dielectric), and two 18 mm long MSLs having a loss of -0.0239 dB/mm. The IL of -2.9 and -2.5 dB is observed at 38 and 41 GHz, respectively. Considering the loss components, the transition loss per a single transition is -0.44 and -0.32 dB at 38 and 41 GHz, respectively.

4. HIGH-GAIN AMPLIFIER MODULE

After removal of two sets of the transitions from the metal case, two amplifier ICs and chip capacitors to prevent low-frequency oscillation are mounted by soldering on the RT5880 substrate with transitions. The DC bias board is embedded in its back side. The assembly photograph of the high-gain amplifier module was as shown in Fig. 4(a). The overall module size is $79 \times 42 \times 32\,\text{mm}^3$ S-parameters of the fabricated high-gain amplifier module were measured at a drain supply voltage of 5 V and total DC current of 1,000 mA and the measured performance is presented in Fig. 4(b), compared to characteristics plotted from a datasheet of the amplifier IC [11]. The measured gain (M-S21) of more than 39.7 dB is achieved between 38 to 41 GHz. At 38.7 GHz, the maximum gain of 44.25 dB is obtained in spite of a little different DC bias conditions from the datasheet and assembly loss such as soldering and transitions. Compared to RLs (IC-S11 and IC-S22) of one amplifier IC, the measured output RL (M-S22) and input one (M-S11) of the high-gain module are improved and degraded, respectively. The reason comes from assembly quality of the substrate with

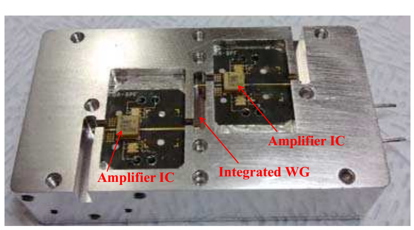


(a)

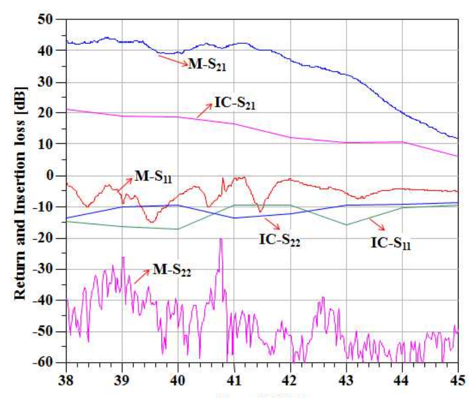


(b)

Figure 3: (a) Photograph of the fabricated transitions assembled in the metal case and (b) measured loss characteristics of the fabricated transitions [AD.: an adapter, TR.: the fabricated transitions, and an inset: the photograph of the adapter].



(a)



(b)

Figure 4: (a) Photo of the interior of the fabricated high-gain amplifier module and (b) its measured performances compared to AMMP-6441 characteristics from a data sheet [M: measurement and IC: the results from a data sheet of an amplifier IC (AMMP-6441)].

WR22-to-MSL transitions. The high-gain module with the gain of over 40 dB was implemented without oscillation. That demonstrates the integrated W/G can suppress the feedback effect in the high-gain amplifier module.

5. CONCLUSIONS

A 40 dB high-gain amplifier module has been presented for millimeter wave applications. In order to suppress oscillation, one WR22 waveguide (WG) is inserted between cavities for mounting chips in the metal case. The high-gain amplifier module cascades two amplifier ICs by using four WR22 WG-to-microstrip line transitions on 5 mil thick RT5880 substrate. The fabricated transition showed the transition loss of less than −0.44 dB per a transition from 35 to 50 GHz. The high-gain amplifier module achieved the gain of more than 39.7 dB from 38 to 41 GHz. At 38.7 GHz, the maximum gain of 44.25 dB was obtained

REFERENCES

1. Tessmann, A., S. Kudszus, T. Feltgen, M. Riessle, C. Sklarczyk, and W. H. Haydl, "A 94 GHz single-chip FMCW radar module for commercial sensor applications," *IEEE MTT-S International Microwave Symposium*, Vol. 3, 1, 851–1854, 2002.
2. Tessmann, A., A. Leuther, M. Kuri, H. Massler, M. Riessle, H. Essen, H. Stanko, R. Sommer, M. Zink, R. Stibal, W. Reinert, and M. Schlechtweg, "220 GHz low-noise amplifier modules for radiometric imaging applications," *The 1st European Microwave Integrated Circuits Conference*, 137–140, 2006.
3. Kim, J.-G., D.-W. Kang, B.-W. Min, and G. M. Rebeiz, "A single-chip 36–38 GHz 4-element transmit/receive phased-array with 5-bit amplitude and phase control," *IEEE MTT-S International Microwave Symposium*, 561–564, 2009.
4. Yaakob, S., N. M. Samsuri, R. Mohamad, N. E. Farid, I. M. Azmi, S. M. M. Hassan, N. Khushairi, S. A. E. A. Rahim, A. I. A. Rahim, A. Rasmi, A. K. Zamzuri, S. M. Idrus, and S. Fan, "Live HD video transmission using 40 GHz radio over fibre downlink system," *IEEE 3rd International Conference on Photonics (ICP)*, 246–249, 2012.
5. Rangan, S., S. R. Theodore, and E. Erkip, "Millimeter wave cellular wireless networks: Potentials and challenges," *Proceedings of the IEEE*, Vol. 102, 366–385, 2014.
6. Tessmann, A., M. Riessle, S. Kudszus, and H. Massler, "A flip-chip packaged coplanar 94 GHz amplifier module with efficient suppression of parasitic substrate effects," *IEEE Microwave and Wireless Components Letters*, Vol. 14, 145–147, 2004.
7. Dhar, J., R. K. Arora, A. Dasgupta, and S. S. Rana, "Enclosure effect on microwave power amplifier," *Progress In Electromagnetics Research C*, Vol. 19, 163–177, 2011.
8. Krems, T., A. Tessmann, W. H. Haydl, C. Schmelz, and P. Heide, "Avoiding cross talk and feedback effects in packaging coplanar millimeter-wave circuits," *IEEE MTT-S International Microwave Symposium*, Vol. 2, 1091–1094, 1998.
9. Beilenhoff, K. and W. Heinrich, "Excitation of the parasitic parallel-plate line mode at coplanar discontinuities," *IEEE MTT-S International Microwave Symposium*, Vol. 3, 1789–1792, 1997.
10. Yook, J.-G., L. P. B. Katehi, R. N. Simons, and K. A. Shalkhauser, "Experimental and theoretical study of parasitic leakage/resonance in a K/Ka-band MMIC package," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, 2403–2410, 1996.
11. Avago Technologies, Available: http://www.avagotech.com.
12. Rogers Corporation, Available: http://www.rogerscorp.com.
13. CST Microwave Studio, Available: https://www.cst.com.