Design of a High-Performance Millimeter-Wave Transmitter Frequency Conversion Module

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***Abstract*—This paper presents the implementation of a millimeter-wave transmitter module characterized by high out-of-band suppression and passband flatness. Utilizing RF link system-level simulation technology, the design optimizes the Intermediate Frequency (IF) input power to the mixer within the link and the filtering circuit design in the IF chain. This optimization achieves a transmitter spurious suppression better than 65 dBc. Furthermore, by analyzing the parasitic inductance of bonding gold wires and conducting a mathematical analysis of the fringe field effects on the parasitic capacitance of PCB metallization patterns, a method for rapid and accurate calculation of PCB parasitic capacitance is realized. This enables swift RF matching design for the millimeter-wave circuit, resulting in a transmitter module with a flatness better than 1 dB over an RF bandwidth of 1 GHz. This module exhibits high spurious suppression and excellent RF flatness, providing a valuable reference for millimeter-wave module design.**

***Keywords*—Frequency conversion module, Millimeter-wave, Suppression, Flatness**

I. INTRODUCTION

The transmitter frequency conversion module, serving as the core component of microwave communication systems, directly impacts system signal quality through its spurious suppression and signal flatness, exerting a decisive influence on overall system performance. High spurious suppression in the transmitter module enhances the signal-to-noise ratio (SNR) of communication systems and increases the detection range of radar systems. Millimeter-wave transmitter frequency conversion modules are widely used in satellite communications, radar detection, and other microwave systems. High flatness of the transmitter module ensures signal quality during wideband signal communication or multi-carrier communication. Therefore, special attention must be paid to transmitter spurious suppression and flatness during the design phase.

Based on Multi-Chip Module (MCM) assembly technology, this paper implements a K-band transmitter frequency conversion module with high suppression and high flatness. The module performs up-conversion from the S-band to the K-band, featuring a maximum instantaneous bandwidth of 1 GHz, transmit channel flatness ≤ 1 dB, transmit spurious suppression ≥ 65 dBc, and an output P1dB ≥ 10 dBm.

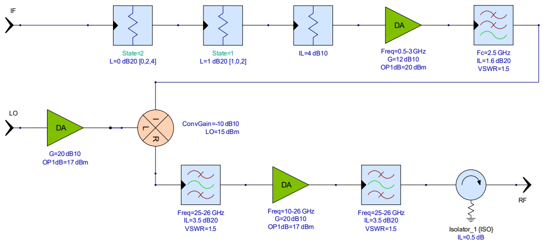
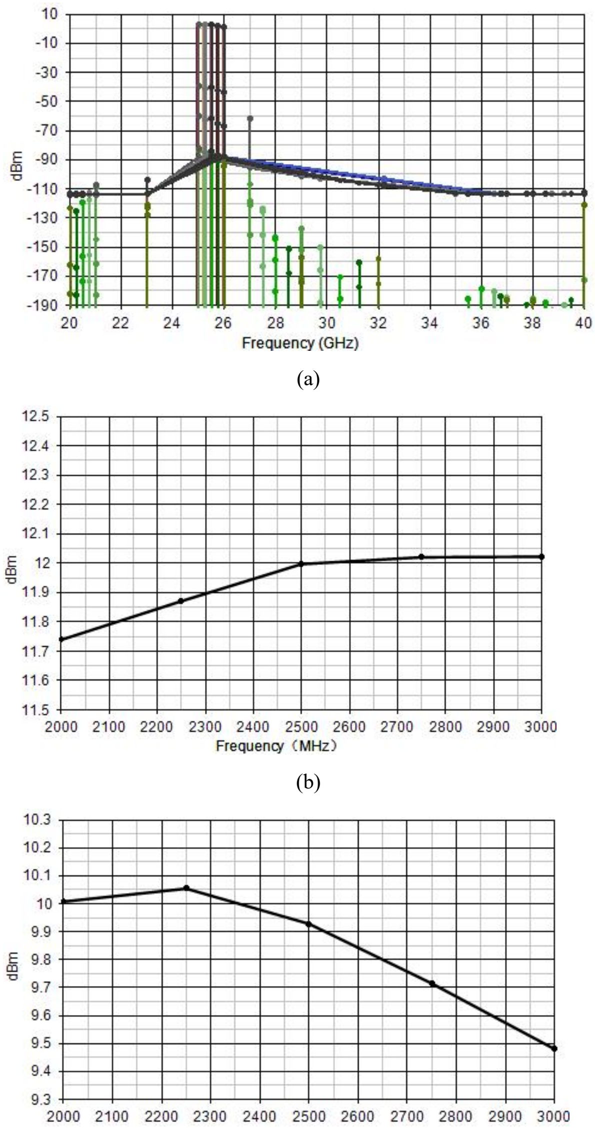


Fig. 1. Block diagram of the K-band millimeter-wave transmitter frequency conversion module link.



(a)

(b)

(c)

Fig. 2. Simulation results of key performance indicators for the transmitter frequency conversion module (a) Simulation result of transmit link

spurious spectrum VS. RF frequency, (b) Simulation result of transmit link output P1dB VS. IF frequency, (c) Simulation result of transmit link flatness VS. IF frequency.

II. Overall Architecture of the Integrated RF Front-End

A. Circuit Scheme Design

The schematic diagram of the millimeter-wave transmitter frequency conversion module link is shown in the Fig. 1.

The K-band millimeter-wave transmitter frequency conversion module achieves low-spurious up-conversion from an S-band IF signal to a K-band RF signal. The input signal at the IF port has a frequency of 2–3 GHz and a power level of -7 dBm. This signal is amplified through the IF chain before entering the mixer. To ensure high RF output P1dB power of the transmit link while reducing the local gain of the RF chain, a mixer chip developed in-house featuring high LO-IF isolation and low LO+2IF spurious products is selected. This allows the IF input power to the mixer to be increased to nearly 0 dBm.

System-level software was used to simulate the key performance indicators of the transmitter frequency conversion module; the simulation results are shown in Fig. 2. According to the simulation results, the proposed up-converter link scheme can achieve performance metrics including spurious suppression better than 65 dBc, output P1dB better than 10 dBm, and link flatness less than 1 dB.

B. PCB Matching Circuit Design

For multi-chip microwave modules, the parasitic inductance of bonding gold wires and the non-50 ohm characteristics of RF chips themselves increase the complexity of RF matching design during the electrical interconnection of RF chips and the PCB. An important method for compensating the electrical characteristics of RF bonding wires is to construct an "L-C-L" matching circuit utilizing the bonding wires and PCB patterns.

The parasitic inductance of a bonding wire can be calculated using the following formula.

$$L = 0.2 \cdot l \cdot \ln[(1+\frac{2h}{d}) + 2\sqrt{\frac{h}{d}(1+\frac{h}{d})}] \qquad (1)$$

In the T-type matching structure shown in Figure 3, the parasitic capacitance of the PCB is typically used to compensate for the bonding wire inductance. The traditional parallel-plate capacitor calculation formula does not account for the effect of fringe fields on the capacitance value. For microwave PCBs used in matching circuits, where the substrate thickness is comparable to the planar physical dimensions, the proportion of parasitic capacitance contributed by fringe effects relative to that generated by the upper and lower electrodes increases significantly, thus amplifying the impact of fringe effects, as illustrated in Fig. 4. Therefore, a detailed analysis of the influence of fringe effects is necessary for the rapid and accurate calculation of PCB parasitic capacitance.

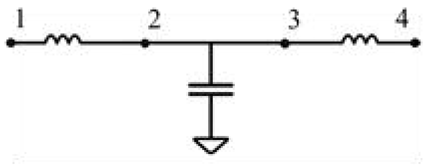


Fig. 3. Schematic diagram of the T-type matching circuit.

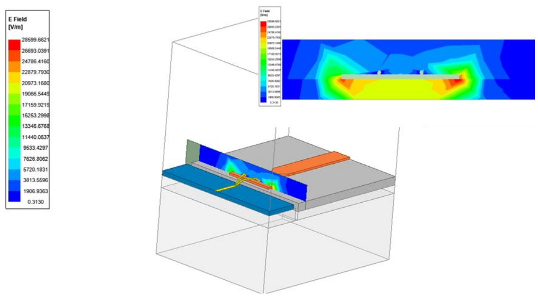


Fig. 4. Example of electric field distribution in a PCB matching metallization pattern.

Li et al. from Southwest University utilized conformal mapping and Green's function methods to estimate the impact of fringe effects on parasitic capacitance for a single-sided infinite length structure. This paper further extends this derivation to obtain a calculation formula for the capacitance of a metallic patch on a PCB with finite length l_1, finite width l_2, and substrate thickness d.

$$C = \frac{Q}{\Delta U} = \frac{Q}{2U_0} = \frac{\varepsilon l_1 l_2}{d} \times \left\{ \frac{2d\left[\ln\left(e^{-\frac{\pi l_1}{2d}} + e^{\frac{\pi l_1}{2d}}\right) + \ln 2\right]}{\pi l_1} \right\} \qquad (2)$$

Using Formula 2, the parasitic capacitance values for patterns of different lengths on a microwave PCB with a line width of 0.4 mm, substrate thickness of 10 mil, and dielectric constant of 3 were calculated. These results were compared with calculations that neglect fringe effects; the comparison results are shown in Fig. 5 [1]. The comparison demonstrates that fringe effects increase the PCB parasitic capacitance value.

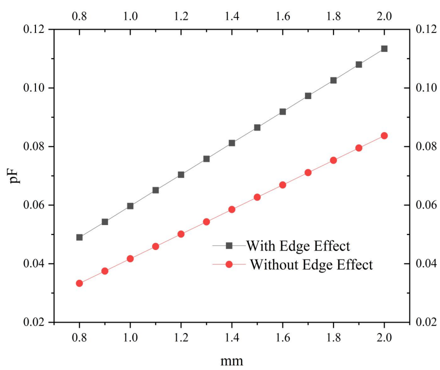
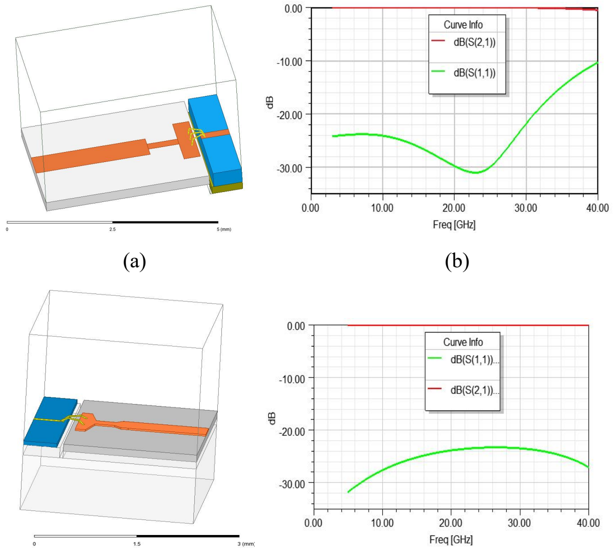


Fig. 5. Comparison of calculated capacitance values considering fringe effects versus those neglecting fringe effects.



(a) (b)

(c) (d)

Fig. 6. Simulation models and results for key interconnection locations (a) Simulation model of MEMS filter-to-PCB bonding interconnection, (b) Simulation result of MEMS filter-to-PCB bonding interconnection, (c)Simulation model of GaAs chip-to-PCB bonding interconnection, (d)Simulation result of GaAs chip-to-PCB bonding interconnection.

Based on calculations of the parasitic inductance of bonding gold wires and the parasitic capacitance of the PCB, simulations were performed for the bonding interconnection structures of key devices (isolator to PCB, Gallium Arsenide (GaAs) chip to PCB) in the millimeter-wave circuit. The simulation models and results are shown in Fig. 6.

The simulation results in Fig. 6 indicate that within the operating band, the RF return loss of the bonding transition structure is better than -20 dB, corresponding to a voltage standing wave ratio (VSWR) better than 1.1. According to literature [2], such an interconnection structure has minimal impact on chip performance and allows for effective utilization of the RF chip's capabilities.

III. Transmit Up-Conversion Test Results and Analysis

The measured data for the transmitter frequency conversion module are listed in Table I [3].

TABLE I. MEASURED PERFORMANCE OF THE K-BAND TILE-BASED T/R MODULE

Parameter	***Value***
Transmit Gain (dB)	31 ~ 33
Transmit Flatness (dB)	0.9
Transmit Spurious Suppression (dBc)	65
Output Power at 1 dB Compression (P1dB) (dBm)	11.5

IV. Conclusion

This paper introduced a K-band MCM transmitter frequency conversion module. Measured results demonstrate that within the operating band, the module achieves an output P1dB power of 11.5 dBm, a gain flatness of 0.9 dB, a conversion gain of 31–33 dB, and an output spurious suppression of 65 dBc, meeting the requirements for engineering applications. The module exhibits high spurious suppression and excellent flatness, holding significant value for practical engineering applications.

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