Optimization of spaceflight millimeter-wave impedance matching networks using laser trimming

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Abstract

Realizing packaged state-of-the-art performance of monolithic microwave integrated circuits (MMICs) operating at millimeter wavelengths presents significant challenges in terms of electrical interface circuitry and physical construction. For instance, even with the aid of modern electromagnetic simulation tools, modeling the interaction between the MMIC and its package embedding circuit can lack the necessary precision to achieve optimum device performance. Physical implementation also introduces inaccuracies and requires iterative interface component substitution that can produce variable results, is invasive and risks damaging the MMIC. This paper describes a novel method for in situ optimization of packaged millimeter-wave devices using a pulsed ultraviolet laser to remove pre-selected areas of interface circuit metallization. The method was successfully demonstrated through the optimization of a 183 GHz low noise amplifier destined for use on the MetOp-SG meteorological satellite series. An improvement in amplifier output return loss from an average of 12.9 dB to 22.7 dB was achieved across an operational frequency range of 175–191 GHz and the improved circuit reproduced. We believe that our in situ tuning technique can be applied more widely to planar millimeter-wave interface circuits that are critical in achieving optimum device performance.

Introduction

Monolithic microwave integrated circuits (MMICs) often require a transition from their planar form to a waveguide in order to effectively couple input and output signals. This is usually achieved through the application of a waveguide-to-microstrip (WG-MS) transition that transforms the impedance of the waveguide channel to the optimal conjugate impedance of the MMIC input or output port. At millimeter wavelengths, the WG-MS transition is typically fabricated from a thin film gold conductive layer, ∼3 μm in thickness, which is deposited onto a thin, <100 μm, quartz or alumina substrate and then suitably patterned to form a sequence of distributed elements [1–3].

Using WG-MS transitions at frequencies higher than 100 GHz presents three particular challenges: (1) due to the uncertainties in pre-packaging on-wafer probing, it is often difficult to determine precisely the optimal impedance required by the MMIC [4, 5]; (2) simulating the interaction between the MMIC and the WG-MS transition is highly complex and thus prone to error; (3) once installed, the fabricated transition cannot be tuned in order to optimize the device packaged performance, i.e. to correct for the errors that may arise from 1 and 2.

A tuning technique commonly used in planar matching networks at lower frequencies incorporates patch tuning elements to modify transmission line impedances and lengths [6–8]. Unfortunately, this technique cannot readily be implemented at millimeter wavelengths ranges due to the smaller feature size and assembly complexity of the related circuitry. To achieve performance requirements, it is therefore often necessary to assemble (package) and test multiple design variations, and perform a subsequent device selection, or to sequentially disassemble and substitute components. Clearly, these approaches are very inefficient, wasteful, and costly. Additionally, the inherent variability of MMIC performance observed at millimeter wavelengths [1, 9] can affect packaged performance repeatability and often mask the effect of applied changes.

We address the above difficulties through the demonstration of a novel empirical method of circuit tuning that allows the in situ optimization of millimeter-wave packaged device microstrip and coplanar impedance-matching elements. Our approach makes use of laser “maching” to trim the planar interface circuit conductor area and thereby allowing the application of additional inductance and resistance in pre-selected areas of a matching network. Being a subtractive process, it is not possible to add material and this can limit the extent of circuit tuning that is achievable. Whilst laser trimming is already used for electronic component tuning, e.g.
thin-film resistor [10, 11] and capacitor [12, 13] parameter adjustment, to the best of our knowledge, it has not previously been applied in the in situ optimization of packaged millimeter-wave MMIC devices. Moreover, we have demonstrated that the modified circuit can be transferred to a conventional photolithographic process and used to reproduce optimized performance in similar devices reliably using fully space-qualified processes. This provides advantages for multiple device production and spaceflight applications.

Methodology

In order to demonstrate our in situ tuning technique, we designed and fabricated a WG-MS output transition suitable for packaging with a state-of-the-art low noise amplifier (LNA) MMIC operating at a center frequency of 183 GHz [14, 15] and destined for use in space-borne radiometers aboard the MetOp-SG meteorological satellite series [16, 17]. The design process was as described in [18]. The WG-MS pre-trimming design was performed using HFSS [19] and optimized to the MMIC output impedance requirements obtained from a previous wafer probe measurement performed by the chip supplier [14, 15]. The waveguide channel impedance was $Z_{WG} \approx 489.2$ Ohm at 183 GHz. The output impedance of the MMIC was $Z_{MMIC} \approx 120 + 101j$ Ohm at 183 GHz. The WG-MS transitions were fabricated on a 25 μm-thick quartz substrate with a 3 μm gold conductor layer. Quartz has a dielectric constant ($\varepsilon_r$) of 3.8 [14]. Figure 1 shows the original untrimmed transition assembled onto a 183 GHz LNA.

A calibrated Keysight vector network analyzer (VNA) N5225B with WR-5 waveguide frequency extenders was installed beside a pulsed frequency tripled neodymium-doped yttrium aluminum garnet (Nd:YAG) laser with an output wavelength of 355 nm and as shown in Fig. 2. The LNA comprised a two-part split mechanical housing that when separated allowed access to the device internal components. All microwave circuitry, including the transitions to be trimmed, were contained in a single half that was placed securely on a high-precision (micrometer accuracy) lateral positioning stage. The stage was located beneath an optical inspection microscope and the laser system and, with the use of an integrated camera, allowed accurate positioning of all implemented laser trims. Advanced inspection tools such as scanning electron microscopy imaging were also used upon completion of the “trimming campaign” to validate the initial assessment.

Laser settings were incrementally optimized using spare transition samples. For example, variations of scan speed and repetition rate were used to micromachine the surface with the aim of reducing damage to adjacent and underlying areas. An optimum gold ablation threshold was determined by defining points along a feature to be trimmed and setting the number of pulses applied at each point. During this process, gold metallization on the underside of the quartz dielectric was monitored for unwanted laser ablation, which can lead to explosive evaporation of an epoxy layer used to attach the transition, resulting in the destruction of the assembly. Visual inspection using microscopy guided the optimization of the laser settings to produce a minimal effect on the bottom metallization whilst achieving functionally adequate gold removal on the top metallization.

A packaged LNA S-parameter performance was first measured using the VNA and in situ laser trimming applied to the WG-MS area previously identified as most relevant for tuning. Metal was removed with a single 30 ns laser pulse focused to a diameter of 15 μm, and with a fluence of approximately 6 J/cm². The laser system uses a scanning refractive optic to define the laser cutting area and operational parameters were varied to optimize the ablation of the gold conductor in terms of complete material removal, minimum collateral damage, and sharp edge definition. After each application of laser trimming, the packaged MMIC was re-measured using the VNA. A 15 μm spot size was sufficient for the feature size of the impedance-matching network presented in this paper. However, for other (e.g. higher frequency) matching networks, a better defined
focal area might be needed. This can be easily achieved using higher quality focusing optics [20].

Results

Pre-trimming assessment

The measured output return loss, S22, prior to the trimming campaign was found to be between $-10$ and $-15$ dB for frequencies between 175 and 191 GHz. This resulted in standing waves between the LNA output and a post-amplification down-conversion stage in the MetOp-SG space-borne receiver system engineering model [18]. In turn, this introduced a frequency-dependent gain variation and affected sideband balance, leading to a significantly impaired radiometric performance. The down-converter input is a double sideband Schottky barrier diode mixer with a measured input return loss of 8 dB.

Trimming and removal analysis

A single trimming procedure including the laser ablation, microscopic imaging of the WG-MS transition, S-parameter measurement of the LNA block and decision-making took approximately 30 min. The procedure was initially applied to a spare “test device” LNA as a means of empirically understanding the effect of each gold removal action on the S22 of the packaged device (Fig. 3). The trim areas were preselected to provide control over the series inductance, A, shunt capacitance, B, and a combination of inductance and capacitance, C, of the circuit.

The most effective trim area from an impedance-matching perspective was A, i.e. narrowing the conductor next to the bond to the MMIC. After this initial mapping, a 120 μm-long and 50 μm-wide microstrip line was reduced in width, initially by 11.5 μm (trimming step 1) and subsequently by 15 μm (trimming step 2). Pictures of the transition during the trimming process are shown in Fig. 4. The same figure also shows the initial performance of the LNA with the untrimmed transition (trimming step 0) and the performance improvement of the LNA throughout the trimming process. The magnitude of S22 improved by nearly 19 dB at 178 GHz. The average improvement in the band of interest, 175–191 GHz, was 9.8 dB. The Cartesian plot on Fig. 4 shows that there was no measurable change in the gain of the amplifier after trimming the output transition. The input impedance match, not shown in Fig. 4, was unaffected. The lower S22 reduced the standing wave between the LNA and Schottky mixer such that gain flatness and sideband balance in the receiver were acceptable.

Following trimming, the modified areas were analyzed using energy-dispersive X-ray (EDX) imaging. Figure 5 shows the achieved level of gold removal with only some small (area, $<1 \mu m^2$) remnants of gold remaining in the area of the trim and on the edge of the ablated copper traces. When compared with the signal wavelength, the very small size of gold particles will have little impact upon the signal transmission of the propagating modes. In addition to gold, the EDX image in Fig. 5 reveals the presence of silicon and oxygen from the fused quartz, SiO2, substrate and a low level, 0.29% of argon, which may arise from the deposition of the gold layer of the transition in a partial argon atmosphere.

Reproduction for spaceflight LNAs

As a test of reproducibility, the trimmed transition dimensions were measured, transferred to a photolithographic mask and an equivalent circuit was manufactured. A photograph of the revised structure is shown in Fig. 6. The required performance improvement was exhibited by all LNAs using the new transition: the measured S22 results from two of these new LNAs are shown in Fig. 7. The slightly different shape between the S22 trace of the LNA with the trimmed transition and the S22 trace of the two LNAs with the photographically reproduced transitions is likely due to the superior photolithographic edge definition in the new transition, plus a variation in MMIC performance as previously indicated. The probed S22 of the MMICs inside the original LNA and the two LNAs with the photographically

| A (μm) | B (μm) | C (μm) |
|--------|--------|--------|
| X (width) | 120    | 40     | 122    |
| Y (depth)  | up to 18| up to 45| up to 17|

Fig. 3. Effect of trimming different areas on the WG-MS transition. The black dot on the Smith chart shows the initial measured S22 of the LNA, at the band center, 183.3 GHz. The letters A, B, and C show different trim areas on the circuit, and the corresponding arrows and shaded regions on the Smith chart show the direction of movement of the impedance as the conductor was removed.
reproduced transitions is also shown in Fig. 7. The MMICs on replicated LNA 1 and replicated LNA 2 feature the same design as those on the original LNA, but are from a different wafer.
Conclusion

This paper has presented an empirical trimming solution that provides a significant improvement in achieving packaged millimeter-wave device performance and where analytical design methods alone are insufficient. It offers the previously unavailable path of in situ post-fabrication optimization of matching networks, via small incremental changes to the conductor layer, that are impossible to implement using conventional microassembly techniques. Moreover, it can in principle be applied to other accessible millimeter-wave circuit elements.

The impact of the laser trimming technique could be further enhanced if performed with in situ S-parameter measurements, i.e. where simultaneous laser trimming and device performance characterization is possible. This would allow the execution of faster and potentially refined circuit tuning. However, this is only possible where removal of the device package cover does not in itself impact performance. For instance, simultaneous measurement and laser trimming of a WG-MS transition as described in this paper would not be possible due to the need to separate the waveguide structure in order to gain laser access.

Finally, it is important to stress that the proposed technique is not a substitute for good initial circuit design. It is an empirical method of affording device optimization through the precision trimming of complex and sensitive millimeter-wave circuitry.

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