A Mode-Suppressing Metasurface for Large-Width MMICs Suitable for Tightly-Packaged Millimeter and Submillimeter Heterodyne Receivers

David Monasterio, Nelson Castro, José Pizarro, Francisco Pizarro, and F. Patricio Mena

***Abstract*—When packaging large-width microwave integrated circuits, care has to be taken to avoid structures that could sustain unwanted oscillations. Unfortunately, this situation may not be attainable since large holding cavities are prone to support parasitic waveguide modes that could produce a feedback loop which, in turn, is especially dangerous in high-gain components with poor match with subsequent elements. This letter presents an scalable metasurface, implemented as a gap-waveguide perfect magnetic conductor, suitable to overcome this problem in millimeter- and submillimeter-band receivers. The proposed solution was integrated into a compact W-Band (75–110 GHz) receiver where a large chip-width amplifier was placed near a mixer, thus generating oscillations at high-gain levels compromising its operation at some frequencies. The metasurface was incorporated at the top of the amplifier's cavity where it did not only suppressed completely the oscillation, but also increased isolation between components. As a result, the receiver became fully operational as attested by measurements of its noise temperature at the compromised frequencies.**

***Index Terms*—Low-noise amplifiers, microwave amplifiers, millimeter wave devices, microwave integrated circuits, periodic structures, PMC packaging, waveguide package.**

I. Introduction

THE size of monolithic microwave integrated circuits (MMICs) is one of its critical aspects, especially when the dimensions of the chip become comparable with its operational wavelength. In fact, a problem arises when packaging such circuits since the cavity containing the chip could support resonating waveguide modes. These resonances could not only generate transmission problems but are especially dangerous when the circuits present gain. Under this circumstance, they could indeed generate a feedback loop between the output and input of the device, destabilizing a component that could be unconditionally stable otherwise and, at high-gain levels, could provoke an oscillation. This problem becomes more important in the millimeter range and beyond since active MMICs include bias networks that are usually large in size and not easily reducible as the frequency increases [1], [2].

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Two solutions have been described to suppress oscillations in packaged MMICs at high frequencies. One is the use of microwave dielectric absorbers to attenuate the resonance [3]. The second approach is the use of a gap-waveguide perfect magnetic conductor (PMC) metasurface. Although PMC structures have been used in other packaging applications at frequencies as high as the D band [4], for oscillation suppression has only been successfully tested in frequencies below $50\,\mathrm{GHz}$ [5], [6]. Moreover, these studies were performed on individual amplifiers and not in a functional receiver where interaction with other elements, such as mixers, play an important role.

Recently, we presented a compact W-band heterodyne receiver that uses a commercial low-noise amplifier (LNA) and a custom-made mixer in MMIC form [7]. The LNA, featuring an extensive bias network, has a large chip-width for its operating frequency and its proximity with the mixer resulted in a poor matching producing an oscillation. Although the oscillation was eliminated with the use of a dielectric absorber, it rendered the receiver's performance compromised near to the oscillating frequency due to interactions between the RF input and MMIC cavity. In this letter we demonstrate that a gap-waveguide PMC is a more effective solution since it not only suppresses the oscillation but increases isolation between components.

The excellent performance of the metasurface was further attested by measuring the receiver's noise temperature at the compromised frequencies. Importantly, the design of the metasurface considered mechanical constraints making it scalable to higher frequencies.

II. Metasurface Design and Integration into the W-Band Heterodyne Module

The compact heterodyne module presented in [7] uses a commercial MMIC LNA [8] of width $a = 2$ mm. Considering that the cut-off frequency of the fundamental unloaded waveguide mode TE_{10} is given by $\frac{c}{2a}$, where c is the speed of light, we find that in the present case it has a value of $74.95\,\mathrm{GHz}$. Since the MMIC occupies only a small fraction of the cavity, this result implies that waveguide modes could propagate in the W-band.

We carried out a simplified electromagnetic analysis of the complete structure that contains the LNA and mixer. The MMICs were replaced with dummy microstrip lines of the same dielectric material forming a continuous line that goes from the input of the LNA to the output of the mixer. The simulation was performed using the full-wave electromagnetic

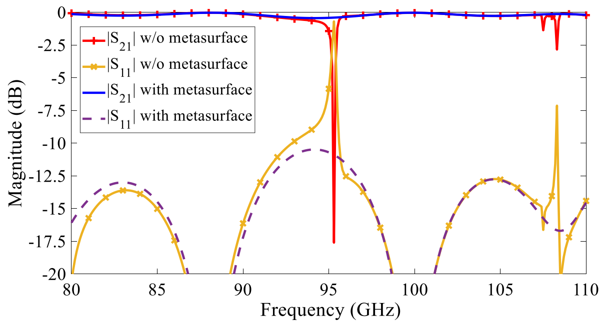

Fig. 1. Simulated $|S_{21}|$ and $|S_{11}|$ parameters of a transmission line inside the LNA and mixer cavities. Simulations were performed with and without the PMC metasurface.

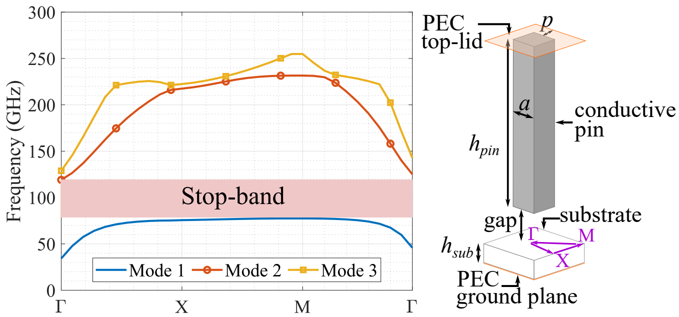

Fig. 2. Dispersion diagram of the proposed structure. Design parameters of the unit cell are $p = 0.105$ mm, $h_{pin} = 0.9$ mm, $gap = 0.2$ mm and $a = 0.15$ mm.

software ANSYS HFSS. Simulation results (Fig. 1) shows a deep resonance present at 95.3 GHz. Additional resonance points were also found at the end of the band but with less impact in the overall transmission, $|S_{21}|$.

To suppress the undesired cavity modes, a metasurface working as a PMC was designed [5]. It consists of a bed-of-nails (BoN) periodic structure which generates a stopband depending on its physical dimensions [9], [10], [11]. The insertion of the PMC boundary condition inside the cavity permits the propagation only where the boundary condition allows it (e.g. between two conductors of the microstrip line) and, by consequence, suppressing all other modes inside the cavity [12], [13].

The designed metasurface must have a stopband within the frequency band we want to suppress the cavity modes. For this, we assess the dispersion diagram obtained on the unit-cell analysis in the irreducible Brillouin zone. Fig. 2 shows the proposed unit-cell and the resulting dispersion diagram for the first three modes. The unit-cell consists of a substrate, separated by an air gap from the conductive pins, of relative permittivity $\varepsilon_r = 12.9$ and height $h_{sub} = 0.1$ mm. We can see that the stopband generated by the metasurface goes from 77.04 to 113.54 GHz.

This stopband is, moreover, robust against fabrication errors. Considering a variation of $\pm 5\,\mu$m for the lateral dimensions of the pins (i.e. a maximum difference of $10\,\mu$m w.r.t. the original dimensions), and increasing the gap to 0.3 mm, the stopband now goes from 77 to 105 GHz, which still suppress the deep resonance present on the structure without the BoN.

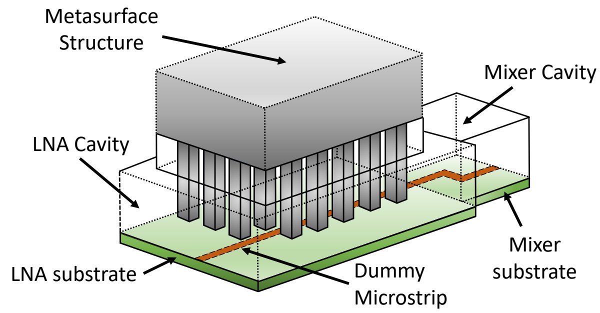

Fig. 3. Representation of the cavities enclosing the amplifier and mixer. The lid containing the artificial magnetic wall is placed above the amplifier he microstrip line includes a bend, only within the mixer cavity, to coincide with the input and output of the amplifier and mixer MMICs, respectively.

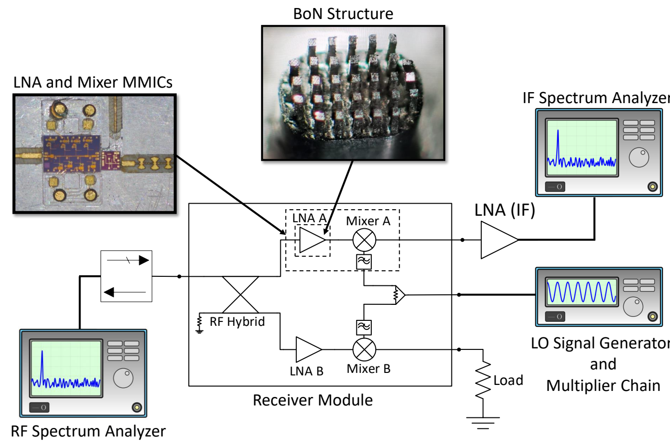

Fig. 4. Diagram of the setup used to measure the instability of the receiver at the RF and IF ports, simultaneously. Two spectrum analyzers were used, an Agilent PXA Signal Analyzer N9030A with a W-Band waveguide harmonic mixer and an Agilent CXA Signal Analyzer N9000A. The insets show the fabricated BoN structure and the LNA and mixer MMICs, respectively.

Another important aspect of the design was that we set the ratio between the length of the pin and its separation from neighboring pins to be less than 4.5, making its construction feasible with the available machining tools. Using this aspect ratio it is possible to implement the design, with appropriate scaling, at even higher frequencies since it is well below ratios used in the construction of other reported high-frequency structures [14].

To check the performance of the metasurface, we incorporated it into the electromagnetic simulation of the cavity. Fig. 1 shows how the resonant peaks of the original simulation were completely suppressed. Finally, the BoN was implemented in a structure that replaced the lid of the existing cavity as illustrated in Fig. 3. It was constructed using a Kern high-precision milling machine with a custom milling tool of 0.2 mm in diameter and is presented in the top inset of Fig. 4.

III. Measurements, Results and Discussion

A. Power Spectrum Measurements

The measurement setup, shown in Fig. 4, allows us to detect any possible oscillation at both ends of the receiver simultaneously. IF amplification was added so that the noise of the spectrum analyzer would not contribute significantly to the measured receiver noise. To simplify the measurements, only one of the two branches of the sideband-separating receiver was tested, working without the use of a 90° IF coupler, thus operating in double-sideband mode. Moreover, they were performed by only biasing the amplifier of the tested branch. Three situations for the LNA cavity were studied, with the original lid, without the lid (open cavity behaving as an ideal absorber), and with the BoN structure. The results are presented using an arbitrary LO frequency of $100\,\mathrm{GHz}$ that allows us to analyze the oscillation frequency in both the RF and IF ports. All measurements where made with the same bias and mixer drive settings, unless indicated otherwise.

1) With original lid: Fig. 5a, blue line, shows the oscillation at the RF input using a bias setting of drain voltage $V_d = 1.4\ \mathrm{V}$ and total drain current $I_d = 28\ \mathrm{mA}$ for the LNA. , probably caused by an interaction between the cavity and a bondwire that may partially excite a higher mode, has a consistent frequency of $97.22\,\mathrm{GHz}$. It is $\sim 2\,\mathrm{GHz}$ above the simulation and has a measured power of $-36\,\mathrm{dBm}$. In contrast, the resonances that were present in the simulations at the end of the band did not manifest in any apparent oscillations. The RF measurement also shows LO signal leakage of the mixers at $100\,\mathrm{GHz}$. Importantly, the gain setting threshold at which the receiver module becomes unstable depends on the LO drive power. This behavior indicates that the instability is dependant not only on the waveguide cavity but also on the mismatch between the amplifier and the mixer. This phenomenon may also explain the discrepancy between the resonance frequency in the measurements and the simulation, since instead of an almost perfect matching microstrip line, reactive elements such as bond-wire and load impedance are present. Another possible cause for this resonant shift might be the construction and mounting imperfections. The IF output (Fig 5b, blue line) presents large harmonic contamination due to saturation produced by the IF amplification of the receiver. Note that, due to saturation of the analog-digital converters of the spectrum analyzer, an internal instrument attenuation was added to properly detect the spectra.

2) With open cavity: When the lid was removed, the oscillation was eliminated in both the RF and IF spectra (Fig. 5a and b, orange lines) due to radiation escaping from the cavity. However, LO leakage to the RF port was suppressed by only $3\,\mathrm{dB}$. We also tested higher LNA bias settings presenting a similar behaviour. It is important to notice that the complete suppression of the instability is not guaranteed for higher gains if a non-ideal absorber is used [5].

3) Metasurface: Measurements using the BoN structure (Fig. 5, red lines) show a complete suppression of the oscillation. Contrary to the situation with the open cavity, the LO leakage power at the RF input is significantly lower and shadowed by the noise floor. This phenomenon can be explained in the following way. Without the metasurface the LO power transfers though the cavity to the RF input, as modes are not suppressed in all directions, ignoring the reverse isolation (S_{12}) of the amplifier, which is usually very high ($35\,\mathrm{dB}$). To prove this hypothesis we repeated the experiment

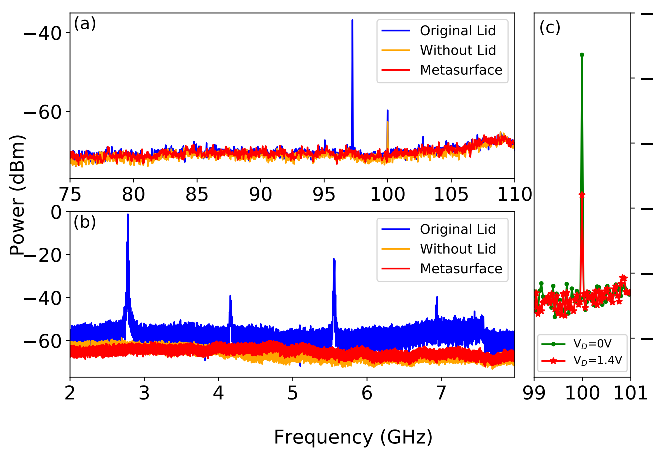

Fig. 5. Power spectrum measurements. (a) RF port of the module. (b) IF port of the module. (c) LO Leakage measurement at the RF input using the metasurface and with two LNA bias settings.

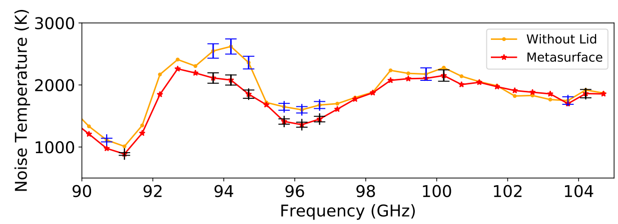

Fig. 6. Measured noise temperature with the top lid removed and the BoN structure. These measurements were made with a fixed IF frequency of $200\,\mathrm{MHz}$ and an integrated spectrum of $100\,\mathrm{MHz}$. Error bars at 1σ are shown in relevant points [16].

with better dynamic range for the instrument and at different bias points. Fig. 5c shows two different bias settings, the first is an unbiased state ($V_d = 0\ \mathrm{V}$ and $I_d = 0\ \mathrm{mA}$), and the second is the bias setting used for the previous measurements. The result shows that LO leakage decreases as the bias increases. This phenomenon corresponds to the expected behavior for the reverse isolation of a HEMT amplifier [15] and was validated using a SPICE simulation of a generic HEMT-based LNA. When we repeated the same experiments using the module with the open cavity, the LO leakage was similar in the biased and unbiased states of the LNA. The measured isolation with metasurface is more that $10\,\mathrm{dB}$ higher than the case when is not used. This result demonstrates that the metasurface has better performance than the open lid, as waveguide modes are suppressed in all directions.

B. Noise Temperature Measurements

Additionally, we measured the receiver's noise temperature in the vicinity of the oscillation frequency using the Y-factor method. The measurement was made using the same configuration of Fig. 4, but with a horn antenna connected at the RF port instead of the spectrum analyzer and isolator. The receiver with the original cavity was not tested since the saturation of the IF chain did not allow performing measurements under the same conditions which would produce non-comparable results.

Fig. 6 shows the measured noise temperature using the metasurface and open cavity. Two aspects are apparent from using the metasurface, absence of oscillations and a slight improvement of the noise temperature from 93.5 to 97.5 GHz. The latter is a consequence of a drop in gain at those frequencies when the cavity is open resulting from, either, a radiating bond-wire or LO leakage affecting the mixer drive point. In any case, both situations are overcome by the metasurface.

IV. Conclusion

We have demonstrated the use of a perfect-magnetic-conductor metasurface, implemented as a BoN structure, to suppresses cavity modes in millimeter-band receivers. The structure was successfully tested in a W-band receiver, not only suppressing a well-defined oscillation but also preventing the leakage of undesired tones through the waveguide cavity. Importantly, the latter advantage is not provided by having the top lid removed (case similar to an ideal microwave absorber), making the metasurface more robust to feedback loops with high gain or when high isolation between components is required. Its excellent properties were also confirmed with noise measurements. They show that the receiver has good performance in the vicinity of the originally compromised frequency. Finally, the design of the metasurface also considered mechanical constraints for the conductive pins making it scalable for use in the submillimeter range, and proved to be robust in terms of fabrication tolerances.

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