

Active Antenna Oscillator Systems in Substrate Integrated Waveguide (SIW) Technology

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Abstract— Active antenna oscillator and coupled oscillator topologies are proposed, whose elements are cavity backed antenna oscillators implemented in substrate integrated waveguide (SIW) technology. Compact single substrate implementations are demonstrated. The cavity backed topology allows one to resolve potential heat dissipation problems, and provides a design parameter to control coupling among the oscillator elements. EM simulation and harmonic balance analysis are used to design the radiating structures and trace the various existing periodic steady state solutions. Measurements of small size prototypes are presented. These compact, low cost implementations could be useful in radar and communication applications.

I. INTRODUCTION

In the last years wireless communications experienced an unprecedented development, spurring a great number of novel applications. In particular, there is a great demand of low profile antennas, especially for space applications.

Coupled oscillator arrays provide a means for introducing electronic beam scanning and generally beam-forming capabilities in antenna arrays, by allowing one to generate desired phase distributions, and to a lesser extent amplitude distributions, among the array elements without requiring phase shifters [1,2]. As a result, phased arrays utilizing the dynamical properties of coupled oscillators have been widely demonstrated [3].

Substrate integrated waveguide (SIW) technology allows one to implement waveguide-like structures using conventional fabrication techniques such as standard PCB technology, in a low cost, compact manner, that permits straightforward integration with planar circuitry. Additional properties of SIW structures include increased shielding, low loss, and good power handling capability [4]. At the moment, a great variety of active and passive devices in SIW technology have been demonstrated [4].

Cavity backed slot and patch antennas have been widely studied in the literature as they offer several design advantages, such as increased efficiency due to surface wave suppression, as well as adequate metal surface to dissipate heat from active devices in large arrays [5-7]. Furthermore, a cavity aperture coupled to active patch and slot loop antenna

oscillators was used in order to improve their phase noise performance [8].

In this work, a compact, single substrate, two element coupled oscillator system, where each element is a SIW cavity backed slot antenna, is demonstrated. The coupling between oscillators is controlled by the aperture size between their respective SIW cavities. Harmonic balance (HB) and EM simulations are combined to design and optimize the performance of the proposed system.

II. SIW CAVITY BACKED ANTENNA OSCILLATOR

The coupled oscillator system presented in this work is formed by an array of two SIW cavity backed slot antenna oscillators.

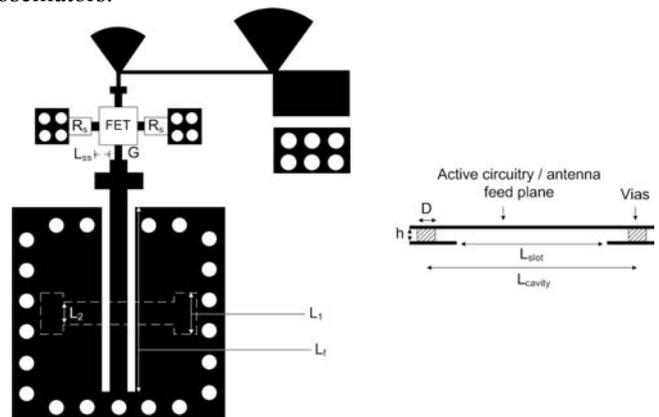


Fig. 1 SIW cavity backed slot antenna oscillator, top view and section

The single cavity backed slot antenna oscillator, shown in Fig. 1, is designed in two steps. First, the passive cavity backed antenna is designed using a FEM-based EM simulator (Ansoft HFSS). In a second step, the active oscillator antenna is designed using a harmonic balance simulator (Agilent ADS). A single substrate prototype has been designed and implemented. The results obtained for the single antenna oscillator have been used as a basis for the design and implementation of a prototype of a two element coupled oscillator system, taking advantage of the coupling between adjacent SIW cavities.

A. Single element SIW cavity backed slot antenna

A SIW cavity backed slot antenna oscillator was considered (Fig. 1) based on the design proposed in [9]. Full wave simulation allows one to carefully design the SIW cavity and the radiating slot, also taking into account the field and current distributions at the frequencies of interest. In particular, both the cavity and the slot have been dimensioned for 10 GHz resonance. The presented topology follows the one presented in [9], with the exception of a smaller cavity and the use of a “dogbone” slot, allowing for a more compact implementation. The antenna is realized on an Arlon 25N substrate with a thickness of 0.508 mm and a dielectric constant of 3.38 at 10 GHz. The substrate is included between two copper planes connected by vias, thus creating a SIW cavity. The slot is etched in the bottom metal layer at the centre of the cavity. The coplanar feed line is extended beyond the slot to match the antenna.

B. Single element SIW cavity backed slot antenna oscillator

Starting from the passive structure, a reflection type oscillator is designed by connecting the cavity to the gate of a NEC NE3210s01 transistor and optimizing the circuit using harmonic balance to obtain a desired oscillation frequency near the cavity resonance frequency (9.91 GHz). The transistor is biased with a drain bias voltage of $V_d=1.5V$ and two resistors are placed between the source terminals of the device and the ground in order to self-bias the circuit. A tuning stub with length L_{ss} (Fig. 1) was used to eliminate unwanted parasitic oscillations and additionally fine tune the oscillation frequency. The HB simulator was made to converge to the oscillating steady state solution by using an auxiliary probe, as described in [10]. The auxiliary probe is only used to avoid the convergence of the HB simulation to the trivial solution which coexists with the periodic one in an oscillator circuit. This auxiliary probe fulfils a condition that avoids affecting the final steady state of the oscillator. Transient simulation was used to verify the stability of the obtained oscillating steady state solutions. The final dimensions selected for the active antenna design are listed in Table 1. A compact, single substrate prototype of the designed circuit was built and measured showing an oscillation frequency of 9.8 GHz. The circuit dissipated 10.5 mW from a 1.5 V supply. Using a probe to capture the radiated signal, the phase noise of the oscillator was measured to be -98 dBc/Hz at 1MHz offset. The phase noise spectrum exhibited a 30dB/dec slope up to and beyond 1MHz offset indicating 1/f noise.

III. COUPLED OSCILLATOR SYSTEM

Coupled oscillator structures can be designed by appropriately coupling the SIW cavities of multiple single element antenna oscillators. EM optimization is necessary to readjust the cavity resonance frequencies that are slightly shifted due to coupling. A two element coupled oscillator system based on SIW slot cavity backed antenna oscillator is shown in Fig. 2.

TABLE I
GEOMETRICAL DIMENSIONS OF THE ACTIVE ANTENNA OSCILLATOR

Parameter	Dimension (mm)
D	1
h	0.508
L_{cavity}	11.8
L_{slot}	10
L_1	2.6
L_2	1.4
L_f	12
L_{ss}	1

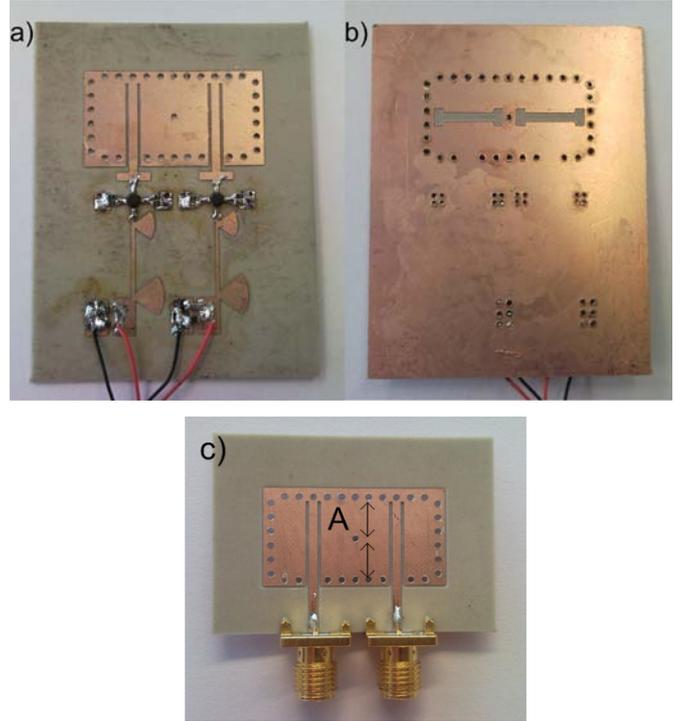


Fig. 2 Two element, X band SIW cavity backed slot array: (a) top (circuit) view of the coupled oscillator system, (b) bottom (antenna) view, (c) top view of the passive coupled SIW cavity backed antennas.

The apertures (A) between the two cavities (Fig. 2c) provide some coupling, which can be controlled by varying the size of A. In this manner one can obtain stronger coupling through the cavities than through radiation coupling, thus allowing for an additional design parameter (A) in order to optimize the dynamical performance of the coupled oscillator system. The width of the apertures (A) has been swept in a parametric simulation, in order to demonstrate the possibility to control the coupling between the SIW cavities. The simulated coupling factor (S_{21} parameter) between the two cavities of Fig. 2 is represented in Fig.3 versus A. As it can be seen, a 4 mm variation of the aperture produces a change in the coupling strength of approximately 7 dB. The variation of the coupling factor occurs smoothly versus the aperture A, which facilitates the control of the coupling factor with the necessary accuracy.

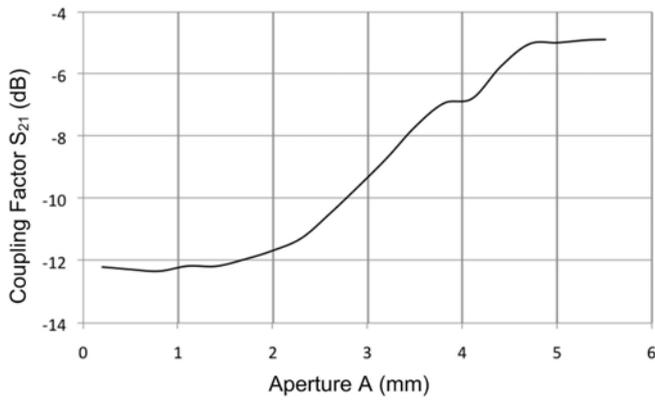


Fig. 3 Coupling factor (S_{21}) for different values of the overall aperture ($2A$) between the cavities.

A. Passive two-element array of cavity backed slot antennas

From the results in Fig.3, two passive 2×1 array prototypes with different coupling between the cavities were built. The passive structure has been designed using two passive cavity backed slot antennas as the one shown in section II.A. The two prototypes were designed to present different coupling factor between the cavities. One of them was designed to have a coupling factor of -9 dB, using an aperture $A=4.9$ mm and the other one was designed to have coupling factor -5 dB with $A=3.2$ mm. In Fig. 4 the measured and simulated S_{21} (coupling factor) curves are plotted.

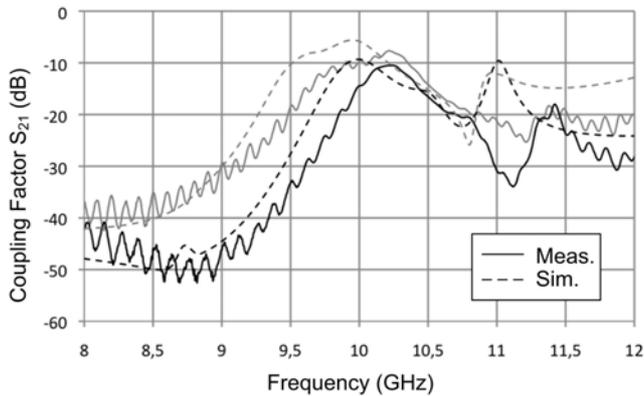


Fig. 4 Measured and simulated coupling factor between the cavities, for $A=4.9$ mm (grey curves) and $A=3.5$ mm (black curves).

As it can be seen, the measured coupling factors curves are shifted towards higher frequencies, reaching the maximum value at 10.2 GHz, and exhibit greater losses than expected. This effect could be due to the different field configuration obtained when apertures are created between the two cavities, and to an inaccurate estimation of the material losses in simulation. From Fig.4 the coupling factors at the resonance frequency of 10.2 GHz for both passive arrays are $S_{21} = -7.6$ dB and $S_{21} = -10.5$ dB respectively in comparison with the simulated ones at 10 GHz of $S_{21} = -5$ dB and $S_{21} = -9$ dB.

B. Active coupled oscillator system

Based on the passive structures described above, a 2×1 array of coupled oscillators has been designed and

implemented. The active devices (NE3210S01) are connected to the cavities input lines (Fig.2) and harmonic balance and transient simulation have been used to optimize the oscillation frequency and study the stability of the system.

When the individual oscillators are introduced into the array their oscillation amplitudes and frequencies will change due to their mutual influence through the SIW coupling structure. A further optimization is necessary in order to readjust the synchronization frequency of the system by acting on the stubs L_{ss} (Fig.1). Based on the optimization results and on the passive cavity measurements one array prototype with $A=3.2$ mm and $L_{ss}=4$ mm exhibiting -5 dB of coupling factor, has been designed and implemented.

In the chosen design the 2×1 array of coupled oscillators is selected to work as a power combining system. This means the oscillators are coupled in such a way that their output powers combined. Theoretically when coupling two identical oscillators in phase one can achieve a 3 dB increase in the total output power with respect to the individual power of each oscillator. The implemented and measured the 2×1 array showed a synchronization frequency of 10.09 GHz. In order to determine the gain obtained by combining the two oscillators output powers, the oscillators were individually biased and their output power and frequencies were measured. The free-running frequencies were found to be $f_1=10.038$ GHz and $f_2=10.024$ GHz respectively. Using a probe to capture the radiated signal, the output power of the two oscillators was measured. The relative measured output powers of the oscillators were P_1 and $P_2 = P_1 + 2.7$ dB which combined to give a total output power of $P_{out} = P_1 + 6.7$ dB $= P_2 + 4$ dB. The differences in the individual oscillators output power are attributed to the limited implementation accuracy and component tolerances.

The measured phase noise of the individual oscillators is $pn_1(@1\text{MHz}) = -97.67$ dBc/Hz and $pn_2(@1\text{MHz}) = -97.43$ dBc/Hz. As expected when combining two oscillators outputs the total phase noise of the system was $pn_{out}(@1\text{MHz}) = -100.8$ dBc/Hz with approximately a 3 dB improvement (Fig.5).

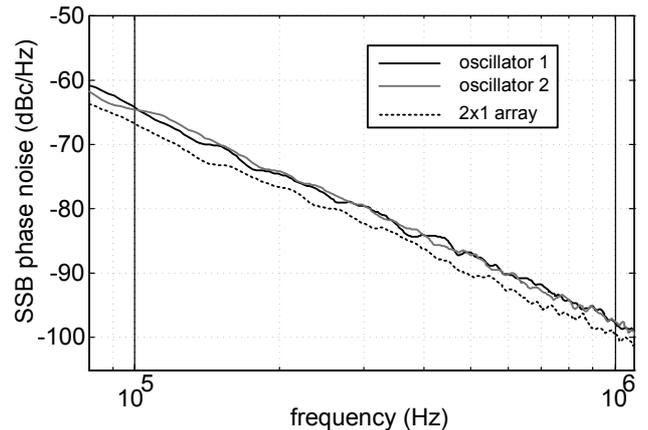


Fig. 5 Measured phase noise of the individual oscillators and of the 2×1 array of coupled oscillators.

Finally the capability of the system to maintain synchronization has been evaluated by obtaining the synchronization bandwidth of the 2×1 array versus the drain

bias voltage V_d . In order to measure this bandwidth one of the oscillators is kept to a fix drain bias voltage $V_{d1}=1.5$ which implies maintaining its free-running frequency to a fixed value f_1 and the other oscillator bias voltage V_{d2} is modified (and consequently its free-running frequency f_2 detuned) in order to detect the limits up to which the systems stays synchronized. In Fig.6 the synchronization bandwidth of the proposed system when detuning both oscillators is presented, showing the system is quite stable.

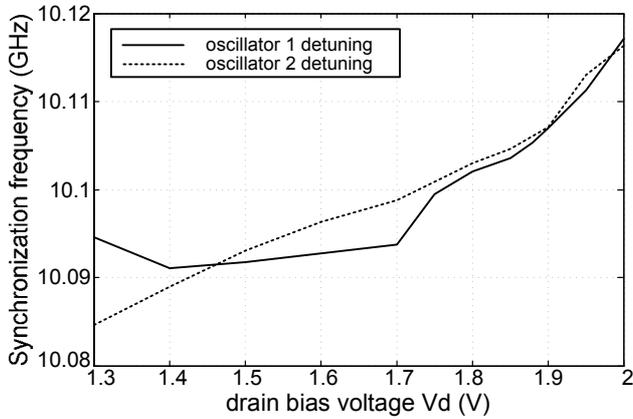


Fig. 6 Synchronization bandwidth of the coupled oscillator system when detuning each of the oscillators.

Finally the radiation patterns of the 2x1 active array were measured in the anechoic chamber. Fig.7 shows the obtained E-plane and H-plane radiation patterns. The product of gain and transmitted power (effective radiated power) is plotted. The E-plane radiation pattern has some ripple which is potentially attributed to the small ground plane. One can verify that the radiation peak is located at broadside indicating that the two oscillators are locked in-phase.

IV. CONCLUSIONS

Low cost, compact, single substrate active antenna oscillators and coupled oscillator systems in SIW technology are proposed. Combined EM simulation and nonlinear simulation tools are used for the design and performance optimization. The SIW cavity backed structure allows one to control the coupling between the oscillator elements of the array modifying the coupling between the cavities. A compact, single substrate prototype of a coupled oscillator system, based on SIW cavity backed slot antennas, was built showing good performance.

ACKNOWLEDGMENT

This work was carried out in the framework of COST Action IC0803-RF / Microwave Communication Subsystems for Emerging Wireless Technologies. The work of A. Georgiadis and A. Collado was also supported by the Spanish Ministry of Science and Innovation project TEC2008-02685/TEC, and grants PTQ-06-02-0555 and PTQ-08-01-06432.

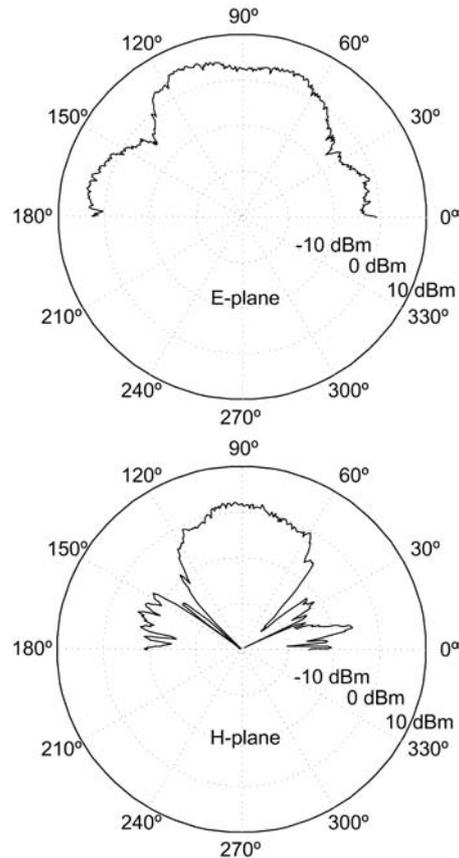


Fig. 7 E-plane and H-plane radiation patterns (effective radiated power) of the 2x1 coupled oscillator array.

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