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ANALYSIS OF THE PERFORMANCE OF INJECTION LOCKED OSCILLATORS IN A DATA TRANSMITTING POLARISATION AGILE ANTENNA APPLICATION

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Abstract—In this work, a polarisation agile antenna based on an array of two injection locked oscillators is presented. The proposed topology provides a theoretical relative phase shift range of 360 degrees between the output signals, which can be easily controlled through two DC voltages. The behaviour of the system is studied, both through simulations and measurements of the manufactured prototype, focusing on the joint performance of the oscillators. The data transmission capabilities of the system are analysed, proposing a solution for phase modulated signals.

1. INTRODUCTION

Due to their capability to dynamically adjust some of their properties to the requirements of each particular scenario, reconfigurable antenna topologies have become a widespread solution in the design of versatile, high performance wireless applications.

Multiple tunable antenna designs can be found in the bibliography, both with passive and active implementations, enabling the variation of different parameters of interest (band of operation [1], radiation pattern [2, 3] or polarisation [4–6]). Active transmitting topologies based on oscillator circuits present important advantages over other possible solutions, such as integrated signal generation, relatively wide continuous phase shift range and ease of control. In [5], a polarisation agile antenna based on injection locked oscillators was presented. A bidimensional array of coupled oscillators is used in [6] to feed a

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polarisation agile phased antenna array, providing both polarisation agility and beam steering.

The related work available in the literature primarily focuses on the phase shifting performance of the circuits and its influence on the overall behaviour of the proposed applications, while the possible data transmission capabilities of these systems are often overlooked. However, in [7], a fixed broadside antenna array fed by free space coupled oscillators is analysed in terms of its performance when the central element is injection locked to a modulated signal. This kind of analysis can be a very useful approach to evaluate the properties of the different solutions with regard to their potential applications in communication systems.

In this paper, a transmitting polarisation agile antenna design is presented, based on an array of two Injection Locked Oscillators (ILO) operating at a frequency of 10.735 GHz. The individual performance of the circuits is compared to their joint behaviour, analysed through simulations of the entire system and measurements carried out on the manufactured prototype. The data transmission possibilities of the circuits are explored and a solution enabling their operation with modulated signals is proposed.

2. CIRCUIT TOPOLOGY

2.1. Polarisation Agile Antenna

The polarisation agile antenna topology is presented in Fig. 1(a). A two port Aperture Coupled Patch Antenna (ACPA) is fed by two identical oscillators with free running frequency $f_0 = 10.735\,\mathrm{GHz}$, which are injection locked to an external reference signal with power P_s, frequency $f_s = f_0$ and phase ϕ_s. This reference signal is provided by a Wilkinson divider with equal power level and phase in both branches.

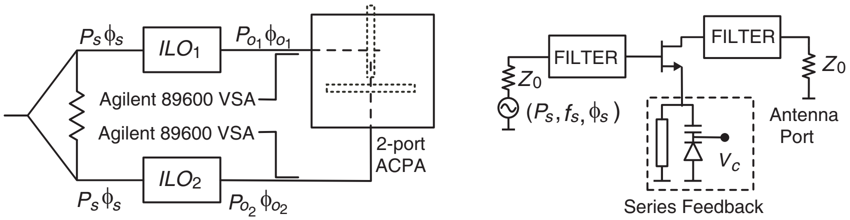

Figure 1. (a) Topology of the polarisation agile antenna. (b) Injection Locked Oscillator circuit diagram.

The power delivered to each antenna port is coupled onto one of its two orthogonal linearly polarised radiating modes so that, by varying the relative phase of both feeding signals, the polarisation can be controlled. Low power samples of the output signals of both ILO circuits are obtained through microstrip directional couplers for phase shift monitoring purposes. The sample signals are simultaneously measured with two Agilent 89600 Vector Signal Analysers (N8201A–N8221A).

2.2. Design of the Injection Locked Oscillator

The circuit diagram of the individual oscillator, designed with an ATF36077 transistor, is shown in Fig. 1(b). The series feedback network at the MESFET source provides negative resistance at the gate to satisfy the oscillation startup condition. The free running frequency f_0 can be varied by tuning the varactor control voltage V_c. Two identical five section hairpin bandpass filters are placed in the input and output ports, in order to avoid possible spurious higher order harmonic synchronisation phenomena. A nonlinear optimisation is carried out to maximise the output power P_o, using the techniques presented in [8].

When the oscillator is injected with an external signal with power P_s, frequency f_s and phase ϕ_s, the frequency of the output signal synchronises with the reference $f_o = f_s$. The oscillation frequency is not affected by the varactor control voltage as long as it remains within the synchronised operation range. Under these conditions, the performance of the circuit in terms of phase shift with respect to the reference signal $\Delta\phi = \phi_o - \phi_s$ and output power P_o, is analysed through harmonic balance simulations [9]. The results for different values of the synchronisation power P_s are shown in Fig. 2. The stable ranges of injection locked operation are determined through envelope transient simulations as presented in [9].

The output power P_o, is slightly dependent on the varactor control voltage and thus, on the established phase shift. Although this dependence increases with the synchronisation power P_s, it may be neglected for most applications since, in the worst case ($P_s = -22\,\mathrm{dBm}$), its variation range remains below 0.2 dB. By tuning the varactor bias voltage, the phase shift $\Delta\phi$, can be varied within a range of nearly 180 degrees for both studied values of the synchronisation power. This phase shift $\Delta\phi$ was found to be increasingly sensitive to the control voltage for smaller values of the synchronisation power P_s. The phase shift ranges of the isolated ILO circuit, calculated in noise-free conditions, are generally reduced in presence of noise, due to the appearance of nonlinear effects when working close to the synchronisation limits [10].

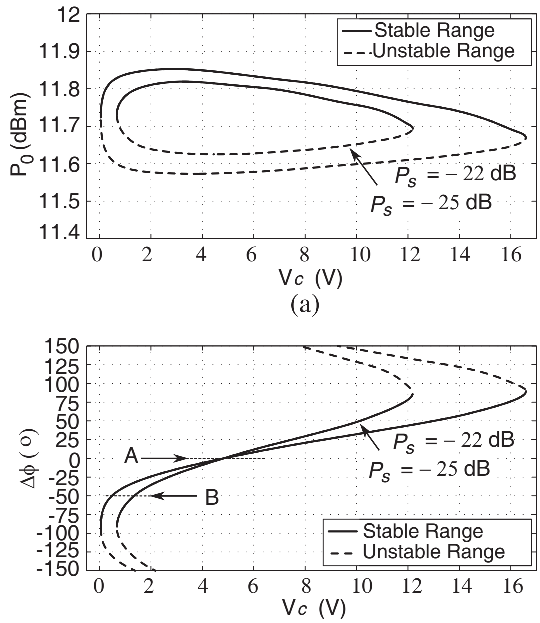

Figure 2. Synchronised operation loci as a function of the control voltage for: (a) The output power and (b) The phase shift, simulated for different synchronisation power levels. The stable regions of operation are also indicated.

3. JOINT PERFORMANCE OF THE INJECTION LOCKED OSCILLATORS

Different arrangements have been proposed when considering the joint operation of several ILO based phase shifter circuits. Different arrangements have been proposed. In coupled topologies, the oscillators are injection locked to the output signals of their neighbours, and the progressive phase distribution can be controlled by adjusting the operation regime of a limited number of elements, which simplifies both the control and the reference signal distribution networks. While this may result in a significant reduction of the implementation complexity in large arrays, it brings about a major drawback for the two element case considered in this work (to feed a polarisation agile antenna or a two element phased array). Without external phase reference, the relative phase shift between the output signals of the oscillators may at most be varied within the range of a single circuit (nearly 180 degrees).

On the other hand, when the oscillators are individually injection locked to an external signal, as depicted in Fig. 1(a), the phase shift each circuit introduces is referred to the external reference and therefore, their ranges of variation remain independent, doubling the range of variation of the relative phase shift between the output signals $\Delta\phi_r = \phi_{o_2} - \phi_{o_1}$, with respect to the aforementioned case.

To attain this double relative phase shift range, a perfect isolation between circuits is required, in order to prevent mutual influences. Any kind of coupling leads to a reduction in the phase shift range, as each circuit synchronises with the vector sum of the external reference signal and the contribution coupled from the other.

In this case, even though the antenna and all the auxiliary networks have been designed to feature high isolation levels (over 45 dB measured at $f_0 = 10.735\,\mathrm{GHz}$), some coupling effects may be noticed in the joint performance of the system. To evaluate the magnitude of these phenomena, electromagnetic simulations of all the microstrip components of the system have been performed, providing a reliable model of these parts at the first five harmonic components of the operation frequency f_0 and DC. The obtained models have been used in the envelope transient simulations carried out to assess the behaviour of the complete system.

The simulation consists of a sweep of the control voltage of ILO_1 (V_{c_1}), throughout its synchronisation range, while keeping the control signal of ILO_2 at a fixed value $V_{c_2} = V_F$. Thus, the influence between the circuits can be analysed by observing the variations of the output power P_{o_2} and phase shift $\Delta\phi_2$ of ILO_2, as the control signal of the other V_{c_1} is swept. This procedure has been repeated for two different operation points of ILO_2, labelled in Fig. 2 as A and B, and with two different power levels of the synchronisation signal P_s. Since the operation properties of one circuit are affected by those of the other, the operation point of ILO_2 is established when ILO_1 is operating at A.

The obtained results are shown in Fig. 3. The variation of the output power P_{o_2} is smaller than a tenth of dB for the studied cases and therefore it may be neglected for most applications.

To simplify the comparison of the phase shift traces, the deviation from the established phase shift value: $D\phi_2(V_{c_1}, V_{c_2} = V_F) = \Delta\phi_2(V_{c_1}, V_{c_2} = V_F) - \Delta\phi_2(V_{c_1} = V_A, V_{c_2} = V_F)$, has been represented in Fig. 3(b). As the operation point of ILO_2 was established for $V_{c_1} = V_A \approx 4.83\,\mathrm{V}$, at this point the phase shift value is the desired and hence the deviation is zero for all the traces.

The deviation is found to be greater in the operation point B than in A. For $V_{c_2} = V_B$, the deviation varies within a range of about

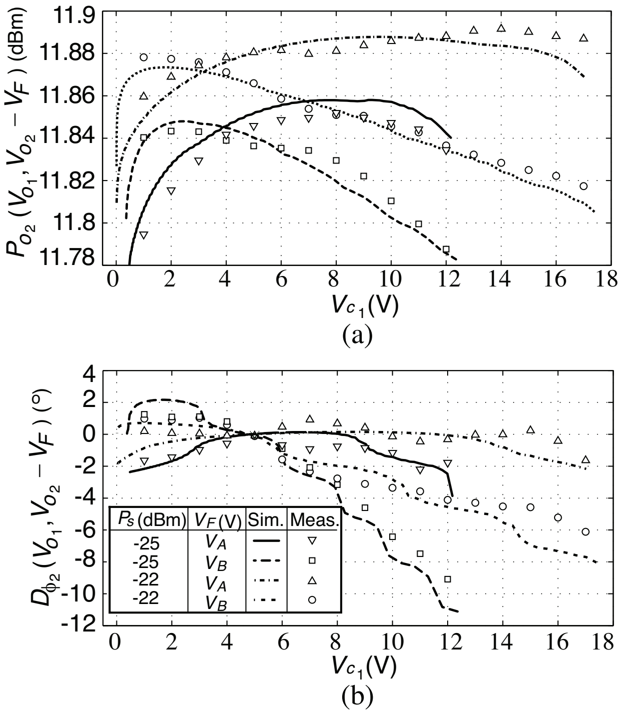

Figure 3. Variation of the output power P_{o_2} and the phase shift $\Delta\phi_2$ of ILO_2, when its control voltage is kept at a fixed point $V_{c_2} = V_F$, as a function of the control voltage of ILO_1 (V_{c_1}). The measured values are shown together with the simulation results.

13 degrees for $P_s = -25$ dBm and about 9 for $P_s = -22$ dBm. For $V_{c_2} = V_A$, the deviation varies within a range of around 4 degrees for $P_s = -25$ dBm and 2 degrees for $P_s = -22$ dBm. For higher values of the synchronisation power P_s, the deviation is reduced as the power of the contribution coming from the other circuit is weaker with regard to the external reference.

The mutual influence observed can be avoided by adjusting the control voltages of both circuits simultaneously, instead of just applying separately the control values corresponding to the isolated operation. Nonetheless, this mutual influence results in somewhat overlapped phase shift ranges in which, while some relative phase shift values are repeated (they can be tuned with more than one pair (V_{c_1}, V_{c_2})), others become unavailable, leading to a reduction in the overall relative phase shift range. Whereas the high isolation obtained in the auxiliary networks enables a highly independent performance of the injection locked oscillators, more significant coupling levels would give rise to severe contractions in the relative phase shift range.

4. DATA TRANSMISSION CAPABILITIES

The proposed solution for the implementation of a polarisation agile antenna based on an array of two injection locked oscillators provides interesting features, such as relatively high output power, ease of phase control and acceptable joint performance. However, the previous analysis only considers the transmission of a single tone, which markedly limits the number of potential applications of the topology, as no information can be broadcast. In this Section, the data transmission possibilities of the system are explored, evaluating its capability to operate with modulated signals.

The performance of injection locked oscillators with modulated signals can be greatly different, depending on the modulation scheme selected. Since the oscillation conditions are satisfied for a given output amplitude, the oscillation usually tends to die out when trying to produce amplitude modulations. Although the oscillation frequency can be modified by tuning the frequency of the synchronisation signal f_s within the range of injection locked operation, this results in detrimental variations of the phase shift $\Delta\phi$ and thus frequency modulation is not appropriate for this kind of system either.

Phase modulations, on the other hand, are relatively easy to obtain by just varying the phase of the synchronisation signal ϕ_s. As the external phase reference is modified, the output phase follows this variation while the circuits remain at the same operation point, maintaining the pre-established phase shifts $\Delta\phi_i$.

The phase variation of the reference signal starts a transient during which the circuits adapt to the new situation. These transients are studied in different conditions through envelope transient simulations [9], since their rise times limit the maximum data rates that can be achieved.

Two envelope transient simulations of the complete system have been performed for $P_s = -25\,\mathrm{dBm}$ and $P_s = -22\,\mathrm{dBm}$. In both simulations OSC_1 was placed at the operation point A and OSC_2 at the operation point B, and the phase reference ϕ_s was varied in steps of 30, 60, 90 and -180 degrees. The phase of the output signals of the circuits ϕ_{o_i} are shown in Fig. 4.

In the first two steps both circuits follow the reference in a similar way. The transients last longer for the circuit placed at the operation point B and the behaviour with both synchronisation power levels

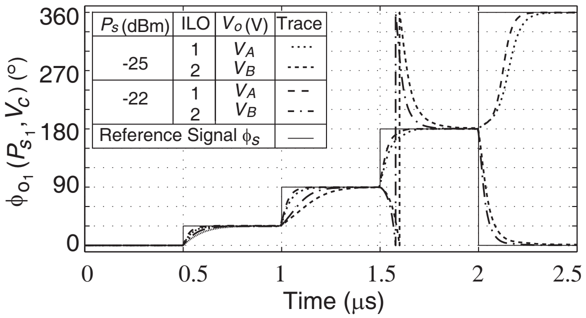

Figure 4. Phase transients of the output signals of the circuits ϕ_{o_i} for $P_s = -25\,\text{dBm}$ and $P_s = -22\,\text{dBm}$. The circuits were placed at the operation points A and B and the reference signal ϕ_s was varied in steps of 30, 60, 90 and -180 degrees.

is comparable. In the third step, the circuits must evolve from the initial phase of 90 degrees to the reference value set at 180 degrees. In this case, the circuit at the operation point A follows the shortest path (from 90 to 180 degrees), while the circuit at the operation point B follows the opposite path (from 90 to -270 degrees) for both synchronisation power levels. Note that the negative phases have been wrapped around in the figure for the sake of clarity. Despite the difference in the lengths of the paths followed by the circuits, the ratio between their rise times are analogous to that of the previous cases. In the last step, the phase reference returns to 0 degrees followed by the circuit at the point B through the same path, while the circuit placed at the operation point A converges to 360 degrees. The highest rise time of the studied transients is $t_{r_{\max}} \approx 240\,\text{ns}$.

The analysis carried out suggests that the proposed topology may be valid for the transmission of phase modulated signals. Further study should be performed in order to determine the maximum rise times and how they are influenced by other parameters of the circuits although, taking into account the previously evaluated transients, BPSK data rates of up to 4 Mbps might be achieved.

5. EXPERIMENTAL RESULTS

A prototype of the system has been manufactured for the experimental validation of the simulated results obtained in Section 3. The output power P_{o_2} and phase shift $\Delta\phi_2$ of ILO_2, have been measured with a vector signal analyser under the specified operating conditions. The measured values have been superimposed in Fig. 3, showing good agreement with the simulated results.

6. CONCLUSION

A polarisation agile antenna design has been presented, fed by an array of two injection locked oscillators, providing relatively high output power (around 11.7 dBm) and ease of control by DC voltages. The proposed topology enables a theoretical relative phase shift range between the output signals of 360 degrees. The influence between circuits has been evaluated through simulations of the complete system, finding a good agreement with the measurements performed on the manufactured prototype. The data transmission possibilities of the topology have been explored, proposing a solution for BPSK modulations at up to 4 Mbps.

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