Enhancement of Locking Range Through Reactive Loading on the Feedback Path

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***Abstract*—Coupled oscillator systems require oscillators with properties that heretofore have not been addressed in oscillator design. Specifically, one needs to achieve wide locking bandwidth-the counterpart to low Q if the oscillator is based on a resonant circuit. This letter introduces an approach to design of wide locking bandwidth by dealing with oscillator design in a feedback format. The specific realization reported here employs a MMIC amplifier with transmission line feedback external to the MMIC. Reactive loads that are weakly coupled to the transmission line allow one to achieve wide locking bandwidth. Results for an implementation at K_a band are provided.**

I. Introduction

ADLER first developed a theory of injection locking of electronic oscillators [1]. Stephan [2] proposed that arrays of oscillators, coupled (mutually injection locked) on a nearest-neighbor basis, would provide an alternative means of generating the linear phase gradation across the face of a phased-array antenna. Subsequently, York extended Adler's theory to a general coupled array thereby providing an analytical tool for coupled oscillator analysis [3]. Since then, a number of workers have explored nearest-neighbor coupled oscillators to the end of producing a phased array that can be controlled from its perimeter rather that with phase shifter control at each internal cell of the array.

Recent studies by Shen and Pearson [4] demonstrate that wide locking bandwidth is essential in achieving effective coupled-oscillator phased arrays. Specifically, a wide locking bandwidth allows steering the antenna to wider look angles by ensuring that the oscillators can find a mutually compatible lock even when the steering requires substantial instantaneous detuning, and the wide locking bandwidth also minimizes the sensitivity of individual oscillator phase to random error in the free-running oscillation frequency of each oscillator cell. Further, Pogorzelski, *et al.* have shown that the transient response time of coupled-oscillator arrays varies with the reciprocal of locking bandwidth [5]. Thus, enhancing the locking bandwidth of the individual cells of an oscillator array improves three important design outcomes: angular steering range, buffering of phase progression from the effects of random errors in free-running frequency, and the transient response time required for the beam to move from one pointing angle to another. Chang, *et al.* have recently developed a method of locking-range enhancement that employs low-frequency feedback to a voltage-controlled oscillator [6]. The complexity of this oscillator cell makes it unusable for coupled-oscillator systems at short wavelengths.

Application of wide locking range oscillators in the pursuit of viable coupled-oscillator beam steering systems requires the design of oscillators in an operating regime that has been heretofore unexplored, to the best of our knowledge. We should note that enhancement of the locking range of an oscillator is a generalization of reducing the quality factor (Q) for an oscillator that derives its frequency from a passive resonant circuit. Thus, the phase noise of the oscillator is degraded as the locking bandwidth is increased. In system applications, the coupled oscillator system is driven from an external oscillator that manifests good phase noise performance, and the output of the coupled oscillator system exhibits phase noise comparable to that of the external source when locked in this way. Cao, *et al.* give a quantitative description of the phase noise relationships in such locking configurations [7].

II. Design Concept

A well-designed MMIC amplifier is unconditionally stable under specified bias conditions. If an appropriate feedback network forms a closed loop from output to input, the resulting circuit will oscillate, making it convenient to use a direct-feedback circuit to building an oscillator. The schematic circuit is shown in Fig. 1. Fig. 1(a) depicts an open-loop configuration of the amplifier and feedback network. If this circuit is designed so that $S_{21} = 1e^{j2n\pi}$, then the circuit will oscillate with the loop closed as shown in Fig. 1(b). This assumes, of course, that the amplifier and feedback network are both matched to 50 Ω so that no mismatch occurs at the feedback connection point.

The well-known Adler theory of injection locking is simple and gives a good approximation for the locking bandwidth if the injection signal is much smaller than the signal generated by the oscillator. *Viz*:

$$\Delta\omega_{\max} = \frac{1}{\Lambda} \cdot \frac{E_1}{E} \tag{1}$$

where $\Delta\omega_{\max}$ is the locking bandwidth, E_1 is the amplitude of injection signal, E is the amplitude of the feedback signal from the oscillator $(E_1 \ll E)$, $\Lambda = d\varphi/d\omega$, and φ is the phase of S_{21}. This expression indicates shows that a more nearly flat phase response widens the locking bandwidth of the oscillator.

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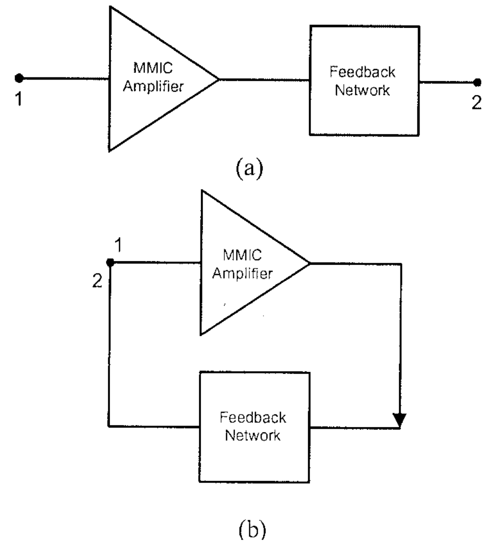

Fig. 1. Component configuration for amplifier-based oscillator (a) open loop and (b) closed loop.

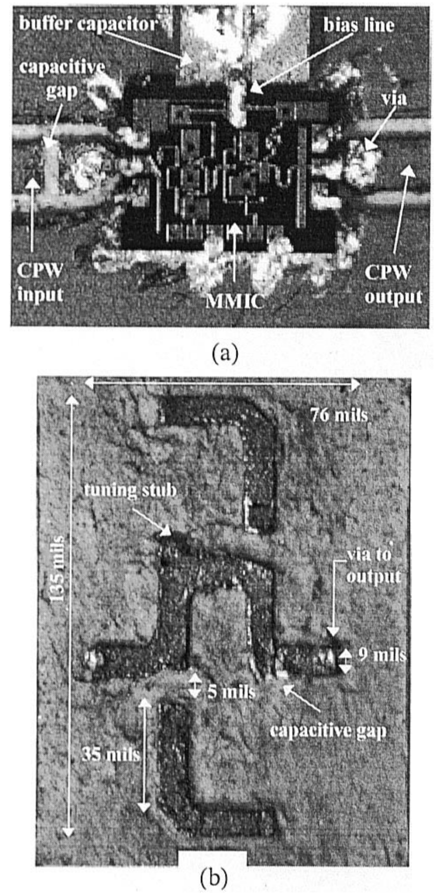

Fig. 2. MMIC-based oscillator with loaded feedback. (a) MMIC/coplanar side and (b) feedback loop on backside with loading stubs board, via holes at the input and output connect the top and bottom of the board.

Therefore, in order to build an oscillator with a large locking bandwidth, one may design the feedback network to flatten the phase response while keeping the oscillation condition satisfied.

This letter reports a mechanism for affecting the phase slope Λ in (1). An open-circuit stub attached in shunt across a transmission line introduces a strong phase dislocation in the transfer function (S_{21}) of the transmission line at the resonant frequency of the stub. If the stub is coupled to the line through weak capacitive coupling, the influence upon the line's transfer function can be made small and can be controlled by the width of the capacitive gap. Fig. 2 shows the two-sided feedback oscillator realization. One observes two half-wave-resonant stubs capacitively coupled to the feedback transmission line in Fig. 2(b). The resonance of these two stubs are staggered slightly in frequency. The position of the stubs along the feedback line is essentially arbitrary, because the coupling is so weak. (We note, too, at the frequency at which this design was implemented is sufficiently high that modeling software is not precise. Thus, the stubs and gaps were adjusted empirically to achieve the desired loading.)

III. Results

Two MMIC-based oscillators were built and their locking range performance compared. The MMIC amplifier employed was a Filtronic Solid State's LMA406. The output power of the MMIC is divided equally between the feedback path and the output load. This ensures that the device operates at saturation. The LMA 406 provides a 14 dBm output at saturation. Hence, the oscillator provides 7 dBm output.

The first oscillator was built using only a transmission line as the feedback element. The second oscillator differed from the first, in that it included loading stubs on the feedback transmission line as shown in Fig. 2. The figure shows the MMIC amplifier with coplanar input and output coupling lines on the top side of the board (2a). The bottom side of the board (Fig. 2(b)) shows a transmission line that connects the output of the amplifier back to the input through via holes that are evident in the pictures. A tab on one corner of the meandered feedback transmission line allows trimming to a precise frequency. A small capacitive gap in this path allows amplitude trimming, as well. The stubs are the L-shaped sections evident at the top and bottom of the backside of the circuit board. The first oscillator is identical to the one shown in Fig. 2 except that the loading stubs are not present on it.

The location and length of the loading stubs are chosen so as to reduce the slope of the phase response in the vicinity of the oscillation frequency. The tuning was performed by adjusting both the resonant frequency of each stub and the coupling between each stub and the transmission line. The tab labeled "tuning stub" in the figure was used to trim the operating frequency of the oscillator.

The simulation results for the (as-built) oscillators are shown in Fig. 3. One sees that the phase response stays close to zero over a significant frequency range near the resonant crossover. Ideally, the response would be monotonic, but fabrication imperfections led to some slope reversal. The locking bandwidth of both oscillators was measured by viewing the tracking between the locking source and the oscillator on a spectrum analyzer until lock was broken. The results are listed in Table I. One can observe substantial improvement in the locking range produced by the slope reduction. Table II displays the upper and lower boundaries of the locking ranges measured. We observe in Fig. 3 that the phase curve is flattest over the cusp just below 36 GHz. One can readily correlate the frequency bounds in Table II to the

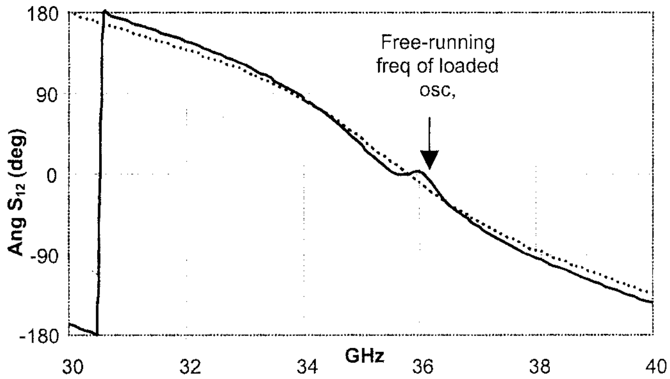

Fig. 3. Simulated phase response of open-loop circuits for the MMIC-based oscillators without loading (dashed line) and with loading (solid line). While the desired free-running frequency is 35.8 GHz, the loaded oscillator runs stably at the rightmost zero phase crossing 36.16 GHz.

TABLE I
MEASURED LOCKING RANGES

P_{inj} (dBm)	Locking Range (MHz) (without stubs)	Locking Range (MHz) (with stubs and tuned)
-15	1	10
-12	3	13
-9	4	25
-6	5	46
-3	9	282
0	13	387

TABLE II
MEASURED LOCKING RANGE

P_{inj} (dBm)	Lower Locking Boundary (GHz)	Upper Locking Boudary (GHz)
-15	35.824	35.834
-12	35.821	35.834
-9	35.814	35.839
-6	35.805	35.851
-3	35.644	35.926
0	35.558	35.945

variation of phase across this cusp. The intended 35.8 GHz design frequency lies to the right of center in this cusp, so that the boundaries in Table II are asymmetric relative to the intended frequency of operation. The free-running frequency of the oscillator is 36.16 GHz, and a second set of locking frequencies around the zero crossing at this frequency (see Fig. 3). The phase slope is relatively steep at this zero crossing, and this resonance is not discussed here. Ideally, for the locking range to center on a fixed frequency requires that the phase variation be quasilinear at the crossing, which designs the locking range. Thus, the fabrication would have to be precise enough to produces monotonic phase variation at the zero crossing.

IV. Conclusions

We have demonstrated that the locking bandwidth of an oscillator cell can be increased by reducing the slope of the phase response of the open-loop prototype of the oscillator. Precise fabrication is required in order to produce a monotonic zero crossing in the phase function while the slope is reduced. Coupled-oscillator arrays based on cells designed by applying the principle here are expected to improve upon existing designs in the extent of phase shift achievable, in tolerance to random errors in the free-running frequency of individual cells, and in their transient response when the beam is steered. The increases the locking range of the oscillator by more than an order of magnitude compared with the unmodified version of the same oscillator. The scheme in [6] produces a doubling of locking range compared with the basic cell from which it is derived. The differences in the basic oscillators limits the conclusions that can be drawn from such a comparison, however. The inability to normalize powers between the two schemes makes comparison of locking range versus injection power meaningless, also.

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