# Comments on "Full 360 Degrees Phase Shifting of Injection-Locked Oscillators"

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In the above letter,[1] Zhang and Daryoush have given a novel design for a subharmonically injection locked local oscillator, consisting of two cascaded suboscillators, by which an analog phase shift of 0° to 360° can be produced. The letter mentioned that the phase shift of the first output will be multiplied by a factor of $n$ at the second suboscillator when it is injection-locked at a subharmonic factor of $n$. The total phase shift at output is given by the following equation

$$\Delta\phi_{\mathrm{LO}} = n\Delta\phi_1 + \Delta\phi_2. \tag{1}$$

The letter also mentioned that no matter how much the second term (i.e., the second suboscillator) contributes, a phase shift of over 360° for the $\Delta\phi_{\mathrm{LO}}$ can always be obtained because the subharmonic factor $n$ is always greater than or equal to 2. On the other hand, as discussed in part III) of the letter, the measured phase shift range is slightly less than 360°. One of the reasons is the high-injection power at the second stage and hence, a wide locking range results. It then boils down to the question whether the second suboscillator is really needed.

In addition, if (1) is true, it can be deduced that for a single-stage $n$th subharmonic injection-locked oscillator, where $n$ is larger than 2, such as 3,4,5,···, the total phase shift can be more than 360°. Therefore, a small frequency tuning within the locking range can provide a full 360° phase shifting. Then there is no longer any need to operate the single-stage subharmonic injection-locked oscillator at the locking boundaries.

It is the authors' experience that when two fundamental locking mode injection-locked oscillators are cascaded together, they can easily provide 280° plus phase shift. The total phase shift for the cascade oscillators is related to the overlapping locking region and is due to the phase shift accumulation in each suboscillator. Here, a simple theory to explain the effect of cascading two suboscillators together is proposed. Transfer characteristics from [1] are used in the discussion, and for simplicity, they are drawn as a rectangle and the phases are assumed to be linear within the locking ranges.

*1) Suboscillators with the Same Transfer Characteristics:* Fig. 1 shows the case when the two suboscillators have the same transfer characteristics, i.e., same locking bandwidth. It consists of three transfer characteristics. Fig. 1(a) and Fig. 1(b) are transfer characteristics of the first suboscillator and the second suboscillator respectively. Fig. 1(c) is the resultant transfer characteristics. When the two suboscillators have the same locking bandwidth. the resultant locking bandwidth does not change. However, due to phase shift accumulation, 180° from each stage [1]–[3], the total phase shift is 360° maximum.

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[1] X. Zhang and A. S. Daryoush, "Full 360° phase shifting of injection-locked oscillators," *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 14–16, Jan. 1993.

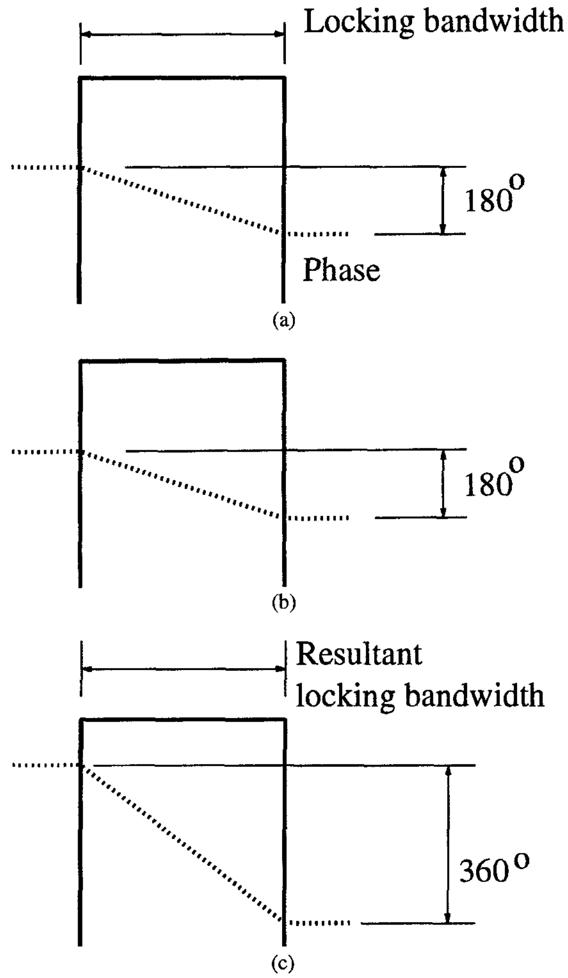


Fig. 1. Resultant of a 2-stage injection-locked oscillator when the two suboscillators have same transfer characteristics. Transfer characteristics of (a) first-stage suboscillator, (b) second-stage suboscillator, and (c) resultant characteristics.

*2) Suboscillators with Different Transfer Characteristics:* Fig. 2 shows the case when the two suboscillators have different locking bandwidths. Suppose that the second suboscillator has a wider locking range than the first one as shown in Fig. 2(a) and in Fig. 2(b), the resultant locking bandwidth is the overlapping region of two locking bandwidths as shown in the Fig. 2(c). However, the resultant phase is 180° $+\Delta\phi$, where $\Delta\phi$ is the phase shift due to the second suboscillator in the resultant locking bandwidth.

Similar argument can be applied for the case when the first-stage suboscillator has a wider locking range than the second one. The resultant locking bandwidth is limited by the second suboscillator which has a smaller locking bandwidth, and the total phase shift is 180° plus the phase shift due to the second-stage suboscillator within the resultant locking bandwidth.

It can also be applied for the case when the locking bandwidths of two suboscillators are misaligned with each other. The resultant locking bandwidth is the overlapping region of the two suboscillators, and the total phase shift is the sum of phase shifts in the resultant locking bandwidth due to the first suboscillator and the second suboscillator. The total phase shift may be greater or smaller than 180°. It depends on the overlapping extent of the two locking bandwidths.

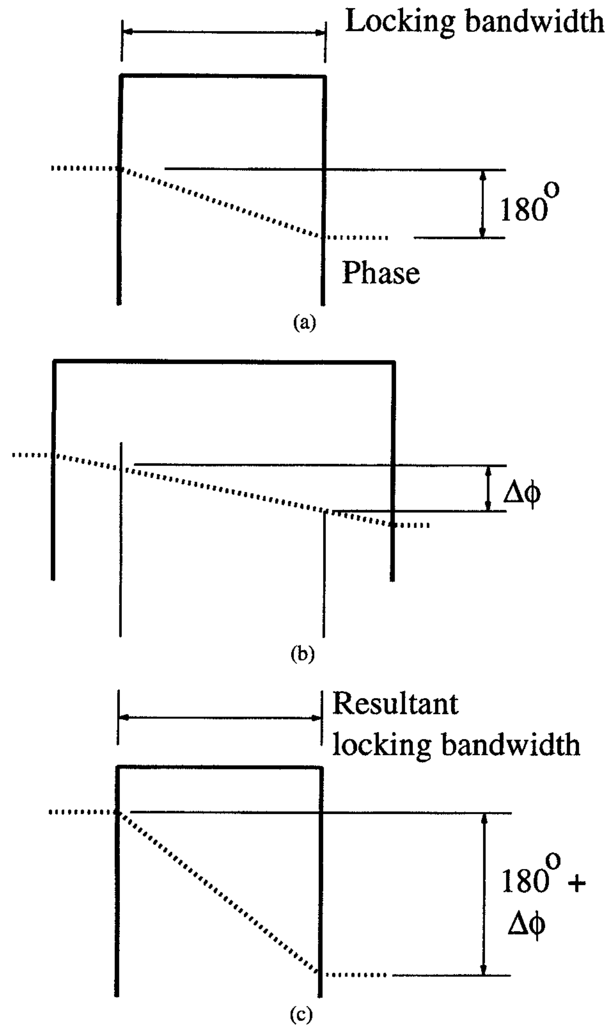


Fig. 2. Resultant of a two-stage injection-locked oscillator when the second suboscillator has a wider locking bandwidth. Transfer characteristic of (a) first-stage suboscillator, (b) second-stage suboscillator, and (c) resultant characteristics.

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## Authors' Reply[2]

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A simple graphical model has been suggested by Wong *et al.* [1] to explain the frequency detuning induced phase shift of two fundamentally injection-locked cascaded suboscillators. We agree with Wong *et al.* the usefulness of their proposed graphical technique. Through the use of this graphical model, the phase shift caused by frequency detuning in the two harmonically related cascaded suboscillators can also be understood. However, we would like to emphasize that great care must be taken in extending this fundamentally locked suboscillators graphical method to harmonically related suboscillators, which was presented by us [2]. In particular, we wish to make the following clarifications concerning the differences between the Wong *et al.* approach [1] and our approach [2].

*Wong et al. Case:* For two cascaded suboscillators, each operating at $f_{lo}$ and synchronized to a frequency reference of $f_{inj} \approx f_{lo}$, the maximum phase shift per stage is ±90° [3]. Therefore, when both suboscillators use the same locking range, then the total phase shift of the suboscillators is ±180° as proposed by Wong *et al.* [1]. They have indicated that a 280° phase shift would be easily demonstrated.

*Zhang and Daryoush Case:* Suboscillator #1 is operating at $f_{lo1}$ while suboscillator #2 is operating at $f_{lo2} \approx nxf_{lo1}$, where $n$ is the subharmonic factor in our reported experiments $n = 2$. When suboscillator #1 is fundamentally locked by a signal $V_{inj}\exp(j\omega_{inj}t + j\phi)$ with a locking range of $\Delta f_1$, the output is denoted by $V_1\exp(j\omega_{inj}t + j\phi_1)$. Here, $\phi_1 = \phi + \phi_{01} + \Delta\phi_1$, where $\phi_{01}$ denotes the phase of suboscillator #1 in the middle of the locking range, caused by intrinsic characteristics of the circuit, and $\Delta\phi_1$ presents the phase shift caused by detuning frequency, $\delta f_1$ [3], i.e.,$\Delta\phi_1 = -\arcsin(2\delta f_1/\Delta f_1)$. Over the full locking range, $\Delta\phi_1$ is only ±90° out of this suboscillator. Moreover, the output of suboscillator #1 will force suboscillator #2 to be subharmonically injection locked to the $f_{inj}$.

The output of suboscillator #2 is presented by $V_2\exp(jn\omega_{inj}t + j\phi_2)$, where $\phi_2 = n\phi_1 + \phi_{02} + \Delta\phi_2$. Once again, $\phi_{02}$ denotes the intrinsic phase shift of suboscillator #2 in the middle of its locking range, caused by intrinsic characteristics of the circuit. The subharmonic locking range for this suboscillator, $\Delta f_2$, is predicted according to the results presented by Daryoush *et al.* [4], and the detuned phase shift, $\Delta\phi_2$, is expressed as $\Delta\phi_2 = -\arcsin(2\delta f_2/\Delta f_2)$. The reason for the presence of "$n$" here is that the injected signal experiences a nonlinear multiplication process to generate a signal at $nf_{inj}$. This nonlinear process transfer the phase characteristics of the injected signal by a multiplication factor of $n$. Note that the controllable phase shifting out of the suboscillator #2, $\Delta\phi_2$, is only ±90° over the full locking range.

The maximum phase shifting range out of the suboscillator assembly can be described now as $\phi_2 = \phi_0 + \Delta\phi_{\mathrm{Total}}$, where $\phi_0 = \phi_{02} + n\phi_{01} + n\phi$, and $\Delta\phi_{\mathrm{Total}} = n \times \Delta\phi_1 + \Delta\phi_2$. Since $\phi_0$ is a constant, the total achievable phase shift is $\Delta\phi_{\mathrm{Total}}$, controlled

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by the frequency tuning of the two suboscillators. This $\Delta\phi_{\text{Total}}$ is the phase shift represented as (1) in our letter [2].

Because both of $\Delta\phi_1$ and $\Delta\phi_2$ have a variation range of 180° and $n$ is equal to or larger than 2, the achievable phase shifting range is $\Delta\phi_{\text{Total}} \leq n \times 180° + 180°$. It should be emphasized that for our case a full 360° phase shifting range is obtained even when the phase shift contribution of, $\Delta\phi_2$, is set to be zero.

To realize an injection locked phase shifter in practice, we fixed the reference frequency of the injection signal and tuned the free-running frequencies of the two suboscillators individually to achieve the necessary detuning frequencies. Since the stability of phase shifting is directly related to the stability of free-running frequency, we suggested in [2] that a dc phase-lock-loop be used in each suboscillator to achieve good phase stability and easy phase control over the full 360° range. The experimental results derived from the use of dc phase-lock-loops will be presented in [5].

*Disagreements with the Wong et al. Interpretation:* As previously explained, in the expression $\Delta\phi_{\text{Total}} = n \times \Delta\phi_1 + \Delta\phi_2$, the factor of "$n$" comes from the nonlinear multiplication effect at the second subharmonically injection-locked suboscillator. In contrast to the interpretation of Wong *et al.*, we want to make the distinction that this expression does *not* imply that a single-stage subharmonically injection-locked oscillator could provide a phase shifting range of $n \times 180°$ at the output by detuning its free-running frequency. It was proved experimentally and theoretically [4], [6] that a single stage subharmonic injection-locked oscillator provides a detuning phase shift of only ±90°. Therefore, the previous expression is true only for cascaded oscillators which are harmonically related, and thus it can not be deduced for only one injection locked oscillator. In fact, suboscillator #2 could be replaced by a frequency multiplier to provide the multiplication factor for phase. But advantages of a subharmonically injection locked oscillator over a multiplier are as follows: a) the linear portions of $\Delta\phi_1$ and $\Delta\phi_2$, i.e., within ±45°, can be used to achieve a linear frequency dependent phase control, and b) the suboscillator provides a much higher locking gain than the conversion loss achieved from a diode multiplier or the limited gain from active multipliers.

To address some of the other questions regarding the use of two cascaded suboscillators, we would like to present an important implication of this technique.

1) *Use in the nondispersive phase shifter:* When higher subharmonic order is used at the second suboscillator ($n \geq 4$), a smaller frequency tuning range at the first stage, i.e., $\Delta\phi_1 \leq \pm 45°$, would result in a nondispersive 0–360° phase shifting and therefore one need not to operate close to the ends of locking range anymore, and the phase shift in the second suboscillator would not be required. This idea has been tested in our latter experiment by using $n = 3$, in which the first suboscillator worked at 4 GHz and the second one operated around 12 GHz [5]. A phase shifting range over 570° was achieved, and the relation of phase versus detuning frequency is quite linear within the range of 360°. The detailed discussion about the locking range of the two suboscillator are discussed in an upcoming paper [5].
2) *Implications of the approach for phased array applications:* In the proposed design, since the output power from the first suboscillator is relatively high (e.g., 10 dBm), this high power assures that the second suboscillator will be effectively subharmonically injection locked. Also, this high power could be split and used to injection lock a number of suboscillators. Part of this output power can also be directed for other system applications. In addition, once dc phase-lock-loops are applied to the cascaded voltage-controlled suboscillators, not only the long term and short term phase noise are greatly reduced, but also the frequency/phase synchronization range becomes significantly increased. Therefore, the cascaded suboscillators can now be used for feeding phase array antennas.

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