VCOs for Mobile Communications

The demand for mobile radio communication revealed a lack of available frequency spectrum below 1 GHz, prompting the use of L band for expanding mobile service. The hairpin shaped, stepped impedance, split-ring resonator, push-push, voltage controlled oscillator can provide small size, low phase noise and broadband tuning for this application.

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Pavio and Smith have shown that push-push oscillators are useful in many system applications [1], having high frequency operation and high output power. Microstrip half wavelength open ring resonators [2,3] are useful above X band, but at lower frequencies hairpin shaped half wavelength resonators [4] are more practical because of their smaller size. Even so, the size often is too large for a compact, MIC, L band oscillator.

Previously we proposed hairpin resonators in the UHF band, in the form of microstrip-line split-ring resonators (MSR's) [5,6], which are composed of a transmission line and a lumped element capacitor. This was evolved into hairpin shaped split-ring resonators with parallel coupled lines to replace the lumped element capacitor.

In this paper we describe an oscillator design suitable for mobile communication applications. It employs hairpin shaped stepped impedance split-ring resonators (SISRs) with parallel coupled lines for even further reduction in the resonator size. SISR's are small enough and have the correct topology for microwave integrated circuits (MIC) and can be used at a much higher frequency range than previously described MSR's. They also accommodate wide tuning range and yield low phase noise.

The push-push oscillators described employ this resonator to achieve compact size, low phase noise and wide oscillation frequency range. In addition, we describe the resonance properties of the new and compact hairpin shaped SISRs as they apply to the push-push voltage controlled oscillator (VCO).

A hairpin resonator with coupled line loading can be made extremely compact for MIC VCOs in L band mobile radio applications.

In the paper we first summarize some structural variations of split-ring resonators and fundamental characteristics, such as resonance properties, are analytically derived. Second, the principle of push-push oscillators built using these resonators is discussed. Finally, to verify this oscillator approach, experimental push-push oscillators with low phase noise or a wide frequency range are described. The experimental performance data were found to be in close agreement with the design expectation.

The Resonator Structure

Various embodiments for the structure of microstrip-line, hairpin resonators are shown in Figure 1. The simplest form (Figure 1a) is the conventional hairpin resonator layout, but it would be too large for a MIC compact mobile radio application at L band or below.

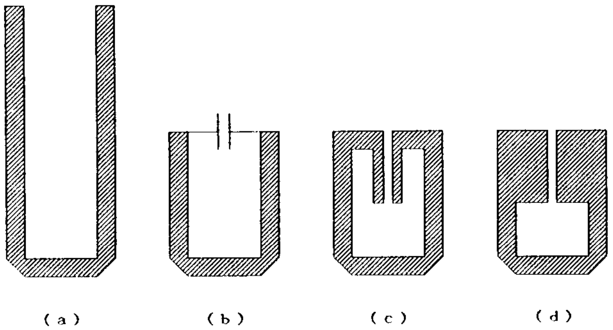

Figure 1. Some structural variations of the hairpin resonator.

This resonator requires no ground connection, often the case of frequency limiting parasitics.

To reduce the size of conventional hairpin resonators, we previously introduced the split-ring resonator (Figure 1b), composed of a transmission hairpin in parallel with a loading capacitor. It should be noted that this resonator structure requires no RF short circuited points, which in other circuits are often the site of parasitic, frequency limiting elements.

Figure 1c shows the hairpin split-ring resonator, an entirely distributed structure in which parallel coupled, open circuited lines replace the lumped capacitor.

Figure 1d shows the new hairpin, stepped impedance, split-ring resonator. To reduce the size of conventional hairpin shaped split-ring resonators, we introduce hairpin shaped SISRs with parallel coupled lines. In the case for which Zs root (Zpe x Zpo), (Figure 2), the total electrical length of these resonators is shorter than that of the conventional designs. This structure can also be applied to a much higher frequency range than that of the lumped element capacitor. Finally this configuration is much more suitable for MICs because it can be made entirely by the photo etching process.

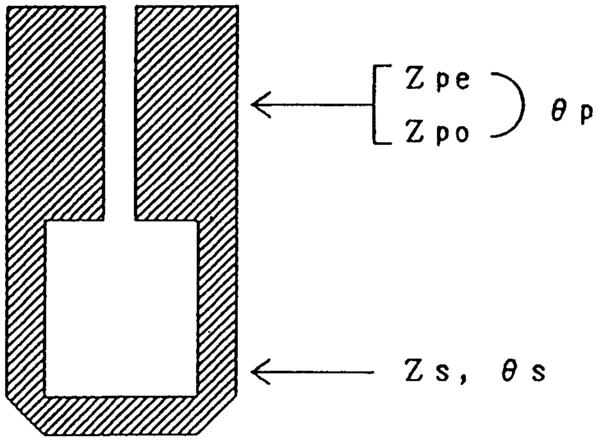

Figure 2. Shortened resonator.

Some advantages of this type of resonator include

1) Size reduction without attendant Q degradation,
2) No parasitics, for broadband, higher frequency,
3) Easy adjustment of resonance frequency.

Resonance Behavior

The equations for the resonance condition are described in Appendix A.

Figure 3 shows the frequency responses of the resonator. These results indicate that this resonator has two remarkable and useful characteristics.

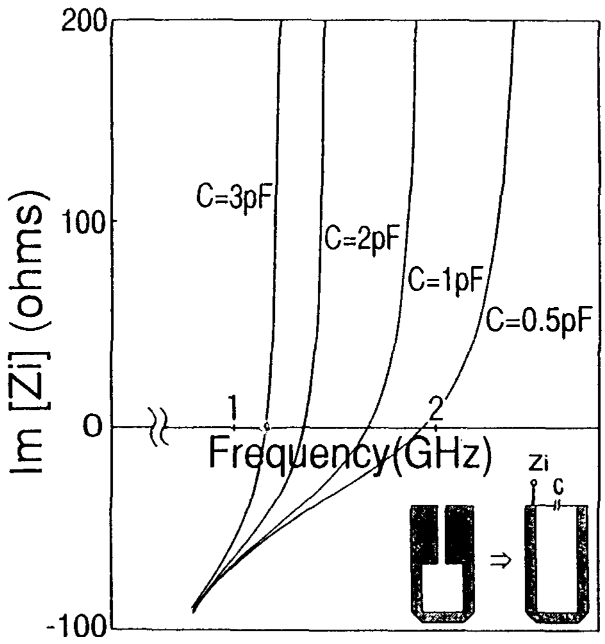

Figure 3. Frequency responses of the resonators.

The closely spaced series and parallel resonance frequencies imply high Q, useful for low phase noise.

The first is that the resonator has both a series and a parallel resonance point and the frequency ratio of the two is small. This implies a high Q, valuable in that it provides low phase noise as a resonator for an RF oscillator circuit.

Resonance also can be varied rapidly with a varactor diode, resulting in wide usable bandwidth.

The second is that the frequency range can be varied over one octave by a conventional tuning varactor without changing the resonator structure, making it suitable for wide band VCOs.

Furthermore, the voltages at the open-circuited output port (1) and (2) are 180 out of phase with each other, an essential property of a resonator for a push-push oscillator.

Fundamental Principle of the Push-Push Oscillator

Push-push oscillators are driven by two identical oscillator circuits which drive a common resonator with signals that are 180 degrees out of phase with each other [8]. Thus, the hairpin oscillator just described is ideal for the push-push oscillator.

Hairpin shaped SISRs having parallel coupled lines with an open-circuited end are considered to have either an odd mode or even mode electromagnetic field distribution in their parallel coupled line section at resonance. The fundamental resonance occurs in the odd mode. The next higher resonance occurs in the even mode. In this way higher mode resonance frequencies alternate between odd and even. Push-push oscillators are realized using the fundamental (lowest resonant frequency) odd mode.

The oscillator used in this design is a common base, Colpitts type. Both oscillator drivers operate at the fundamental resonance frequency, dependent on the hairpin shaped SISRs, but 180 degrees out of phase with one another due to the out of phase voltages at the resonator terminals to which they are connected.

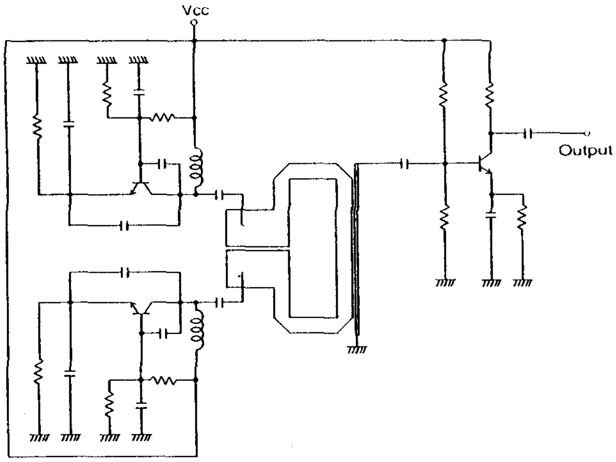

Figure 4. Circuit diagram of the push-push oscillator.

The total power generated by the two oscillator drivers could be summed using various circuits, such as a differential amplifier, balun or rat-race circuits. In this design we used a balun consisting of asymmetrical parallel coupled lines, one of which is part of the hairpin resonator itself. This detail is also shown in Figure 4.

The push-push oscillator combines two identical drivers which operate in antiphase, cancelling common spurious signals and noise.

The total output signal so obtained not only has twice the delivered power of each single ended Colpitts driver, but a much more frequency pure spectrum, since in phase noise power emerging from the two drivers is cancelled by the balanced design of the push-push oscillator. For this reason, push-push oscillators employing hairpin shaped SISRs have the advantage of inherently lower phase noise characteristics than the single ended driver. Furthermore, even mode harmonics are suppressed by the combining process, as noted earlier.

The design should give 35 dB separation for second harmonic, 40 dB was achieved in practice.

Figure 5 is the calculated output spectrum for the combined output power of the oscillator, from which it can be seen that the second harmonic frequency level is expected to be about 35 dB below the fundamental frequency.

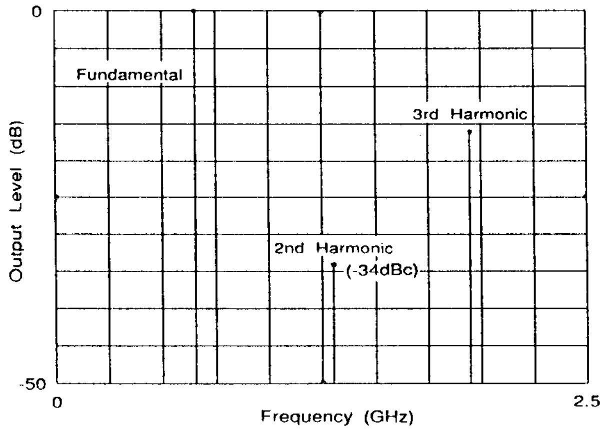

Figure 5. Calculated output spectrum of the push-push oscillator.

Characteristics of Experimental Push-Push Oscillators

Two different types of push-push oscillators using hairpin, shaped stepped impedance, split-ring resonators were experimentally designed and fabricated.

Fixed Oscillator with Low Phase Noise

For this design the design parameters shown below were used.

Eq. 1

$$Zs = 62.6\Omega,\ \theta s = 64^\circ$$
$$Zpe = 39.4\Omega,\ Zpo = 24.9\Omega,$$
$$\theta p = 30^\circ\ (f0{=}750\text{MHz})$$

Figure 6 shows the measured spectral response for the experimental push-push oscillator. Second harmonic suppression was about -40 dB over the band, in good agreement with the theoretical expectation described earlier. Also, the second harmonic was adequately suppressed by the circuit balance.

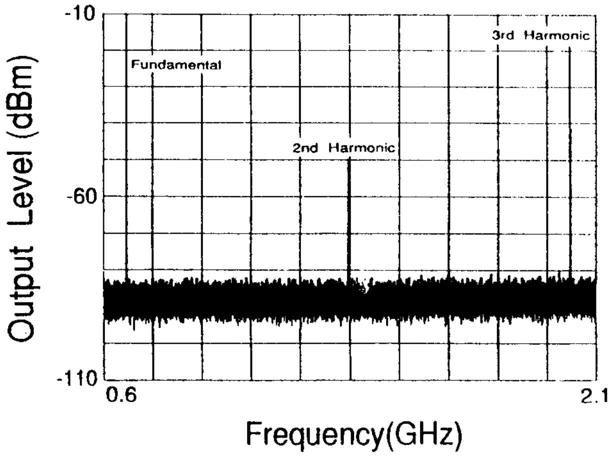

Figure 6. Measured spectral response of the push-push oscillator.

Experimentally, the push-push oscillator's SSB phase noise is 9dB below that of the individual drivers.

A comparison of SSB phase noise between conventional and push-push oscillators is shown in Figure 7. The noise spectrum of the push-push oscillator is superior to that of an individual driver, yielding about a 9 dB improvement for offset frequencies from 1 KHz to 100 KHz.

We feel that this noise enhancement is attributable to two factors. First, when the outputs are combined in antiphase, some external noise is cancelled. Second, the nature of the push-push oscillator is such that the individual drivers are injection locked to each other in operation, thereby causing them to exhibit the lower phase noise of a narrow band injection locked source.

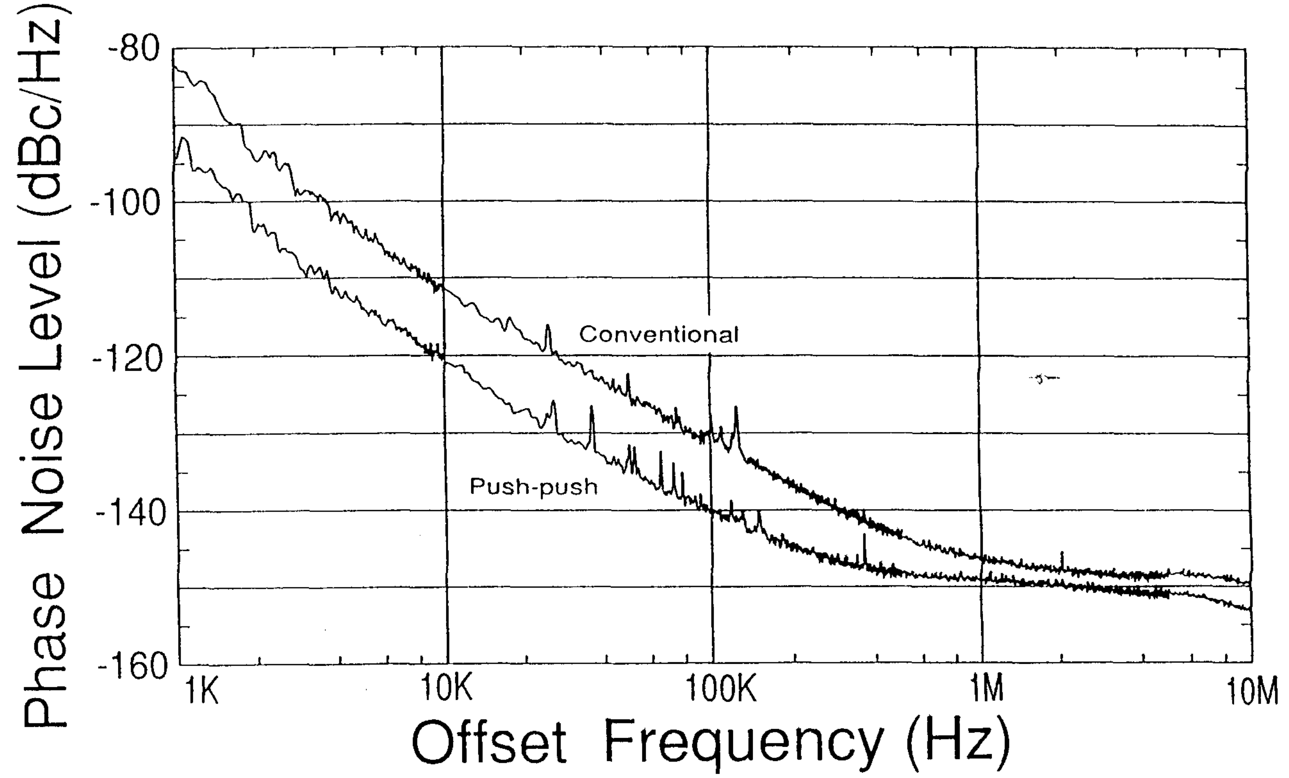

Figure 7. A comparison of SSB phase noise between conventional and push-push oscillators.

Both the antiphase drivers and the injection locked nature of their operation give the push-push oscillator superior phase noise performance.

Frequency drift and single sideband (SSB) phase noise are plotted in Figure 8 as functions of temperature. These results indicate that a frequency drift within 600 KHz and a low phase noise value can be achieved simultaneously from -20 to +60 C when compensation is employed.

Wide Tuning Range VCO

The oscillator designed was extended to a voltage controlled circuit for L band. Figure 9 shows hairpin shaped SISRs with a varactor diode for frequency tuning. By connecting a varactor diode between the parallel coupled lines of the SISRs, a wide band VCO is readily realized. The design parameters of the resonator are described in Equation 2.

Eq. 2

$$Zs = 62.6\Omega,\ \theta s = 70^\circ$$
$$Zpe = 39.4\Omega,\ Zpo = 24.9\Omega,$$
$$\theta p = 30^\circ\ (f0=1.5\text{GHz})$$

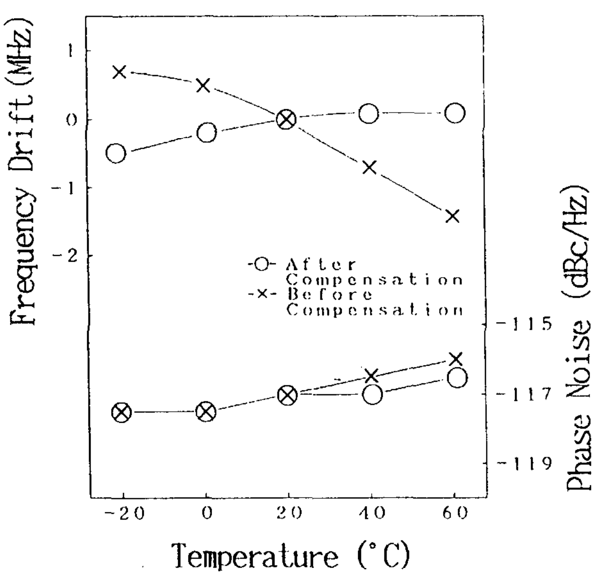

Figure 8. Measured temperature stability of the experimental oscillator.

The tuning range of the circuit as a function of control voltage is shown in Figure 10. Frequency varies from 1.0 GHz to 1.45 GHz over a control voltage range of 2V to 20V. These results indicate that relative variable frequency range is extended by about 35 percent.

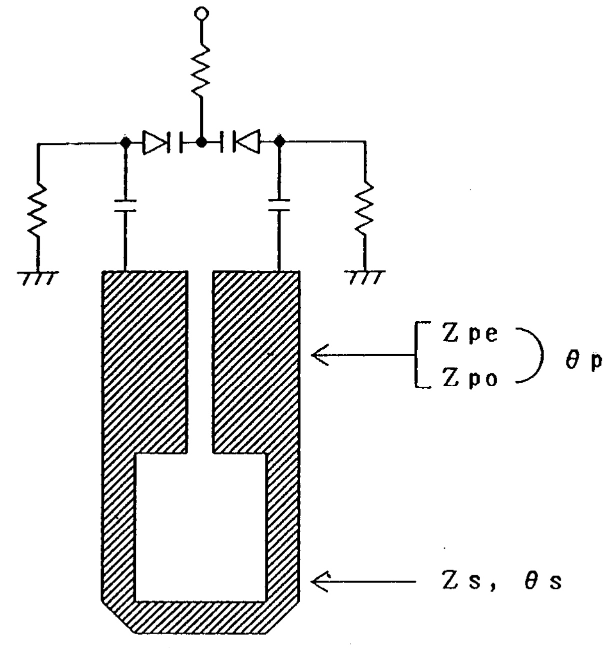

Figure 9. Hairpin shaped stepped impedance split-ring resonators with a varactor diode.

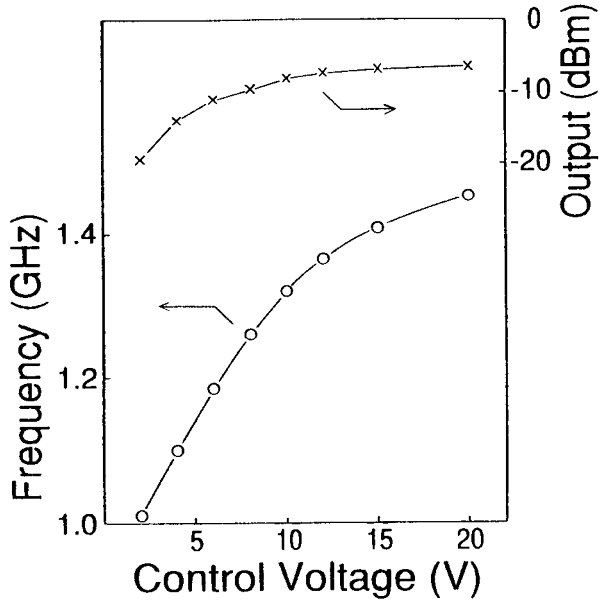

Figure 10. VCO frequency versus control voltage.

Acknowledgment

The authors thank Tomoki Tsumura for his continuous encouragement.

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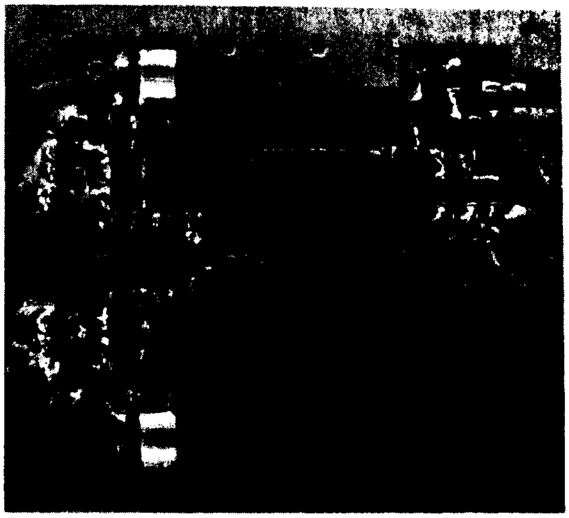

Figure 11. A photograph of the experimental push-push oscillator (size is 37mm x 20mm x 2mm).

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9. Portions of this paper were presented by the authors at the 1991 IEEE MTT International Symposium in a paper entitled "Voltage controlled push-push oscillators using miniaturized hairpin resonators."

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Appendix A. Split-ring Resonance Conditions

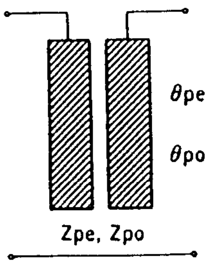
The resonance conditions of split-ring resonators can be obtained using the respective ABCD matrices for a transmission line and a capacitor. The resonance condition of the structure shown in Figure 1b is the same as that of the previously proposed split-ring resonator with a lumped element capacitor [5,6]. The resonator shown in Figure 1d can be analyzed using the following parameters:

Eq. A-1

Z_s	characteristic impedance of the single line,
θ_s	electrical length of the single line,
Z_{pe}, Z_{po}	even- and odd mode impedance of the parallel coupled lines,
θ_{pe}, θ_{po}	even- and odd mode electrical length of the parallel coupled lines.

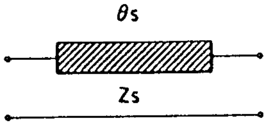
The ABCD matrix for parallel coupled lines with an open end [7] and a transmission line can be expressed as shown in Figure A-1.

Parallel coupled lines



$$\begin{pmatrix} \dfrac{Z_{pe}\cot\theta_{pe}+Z_{po}\cot\theta_{po}}{Z_{pe}\cot\theta_{pe}-Z_{po}\cot\theta_{po}} & -j\dfrac{2Z_{pe}Z_{po}\cot\theta_{pe}\cot\theta_{po}}{Z_{pe}\cot\theta_{pe}-Z_{po}\cot\theta_{po}} \\ j\dfrac{2}{Z_{pe}\cot\theta_{pe}-Z_{po}\cot\theta_{po}} & \dfrac{Z_{pe}\cot\theta_{pe}+Z_{po}\cot\theta_{po}}{Z_{pe}\cot\theta_{pe}-Z_{po}\cot\theta_{po}} \end{pmatrix}$$

A transmission line



$$\begin{pmatrix} \cos\theta_s & jZ_s\sin\theta_s \\ j\dfrac{\sin\theta_s}{Z_s} & \cos\theta_s \end{pmatrix}$$

Figure A-1. Parallel coupled lines, a transmission line and their ABCD matrices.

The resonance condition can be calculated from the input admittance using the total ABCD matrix. The results are as follows:

Eq. A-2

$$\begin{aligned}&(Z_{pe}Z_{po}\cot\theta_{pe}\cot\theta_{po} - Z_s^2)\sin\theta_s\\&+ Z_s(Z_{pe}\cot\theta_{pe} + Z_{po}\cot\theta_{po})\cos\theta_s\\&- Z_s(Z_{pe}\cot\theta_{pe} - Z_{po}\cot\theta_{po}) = 0.\end{aligned}$$

Eq. A-3

When $\theta_{pe}=\theta_{po}=\theta_p$, (1a) is simplified to

$$\begin{aligned}&(Z_{pe}Z_{po}\cot\theta_p - Z_s^2\tan\theta_p)\sin\theta_s\\&+ Z_s(Z_{pe} + Z_{po})\cos\theta_s\\&- Z_s(Z_{pe} - Z_{po}) = 0.\end{aligned}$$

In general, even and odd mode phase velocities are dependent upon properties of the substrate and line structure. We used the condition in Equation 1 to analyze the resonance characteristics in the design described.