Lumped-Constant Line Stretcher For Testing Power Amplifier Stability

To determine the stability of an RF power amplifier, oscillator, or transmitter under harsh conditions, a variable line and fixed attenuator are used to simulate a given VSWR at all phase angles. This article describes a lumped-constant line stretcher using either variable capacitors or inductors.

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Transmitters employing electron tubes were typically narrowband tuned devices. With the advent of the transistor, the RF power amplifier is capable of wideband operation and must therefore be evaluated for stability to avoid interference with other signals. The spectral purity must be maintained in spite of variations in temperature, supply voltage, or load impedance. For applications such as marine, automotive, or portable operation, the antenna may present a severe mismatch to the power amplifier due to the proximity of foreign objects, environmental corrosion, or a pinched coaxial cable. A most stringent test of stability occurs when the power amplifier operates into a high-Q load such as a narrowband duplexer or cavity filter. Commercial mobile transmitters are typically rated to maintain stability into a 3:1 VSWR even under fluctuations of ±20% in supply voltage.

The power amplifier may be tested into a worse case mismatch at all phase angles. This is easily simulated by connecting the amplifier output to an attenuator followed by an adjustable air line terminated in either an open or a short, (Figure 1). Stability is monitored on a spectrum analyzer connected to a directional coupler placed between the power amplifier and the attenuator. Movement of the air line through one-half wavelength will traverse a complete circle around the Smith Chart. The radius of the circle will depend on the size of attenuator used. The mismatch presented by the artificial load is best described using return loss. The value of return loss is simply twice the attenuation of the fixed pad, assuming negligible loss in the adjustable air line. The mismatch in terms of standing wave ratio is given as

$$\text{VSWR} = \coth\left[\frac{\text{attenuator (dB)}}{8.686}\right] \qquad (1)$$

The radius of the mismatch circle on the normalized Smith Chart intersects the right half of the abscissa at the value of the VSWR.

Recently Roderick Blocksome[1] reported on a binary stepped transmission line formed by numerous lengths of coaxial cable and relays. Below 200 MHz the length of a half-wave adjustable air line (>75 cm) becomes so cumbersome that a continuously-variable, lumped-constant version is needed. This article suggests a stretcher using either variable capacitors or inductors instead of transmission lines.

Lumped-Constant Line Stretcher

Consider the network shown in Figure 2. The input impedance is simply the parallel combination of two series circuits L1, C1 and L2, C2.

$$Z\text{in} = j\,\frac{\left(\omega L_1 - \frac{1}{\omega C_1}\right)\left(\omega L_2 - \frac{1}{\omega C_2}\right)}{\omega(L_1 + L_2) - \frac{1}{\omega}\left(\frac{1}{C_1} + \frac{1}{C_2}\right)} \qquad (2)$$

where $\omega = 2\pi f$.

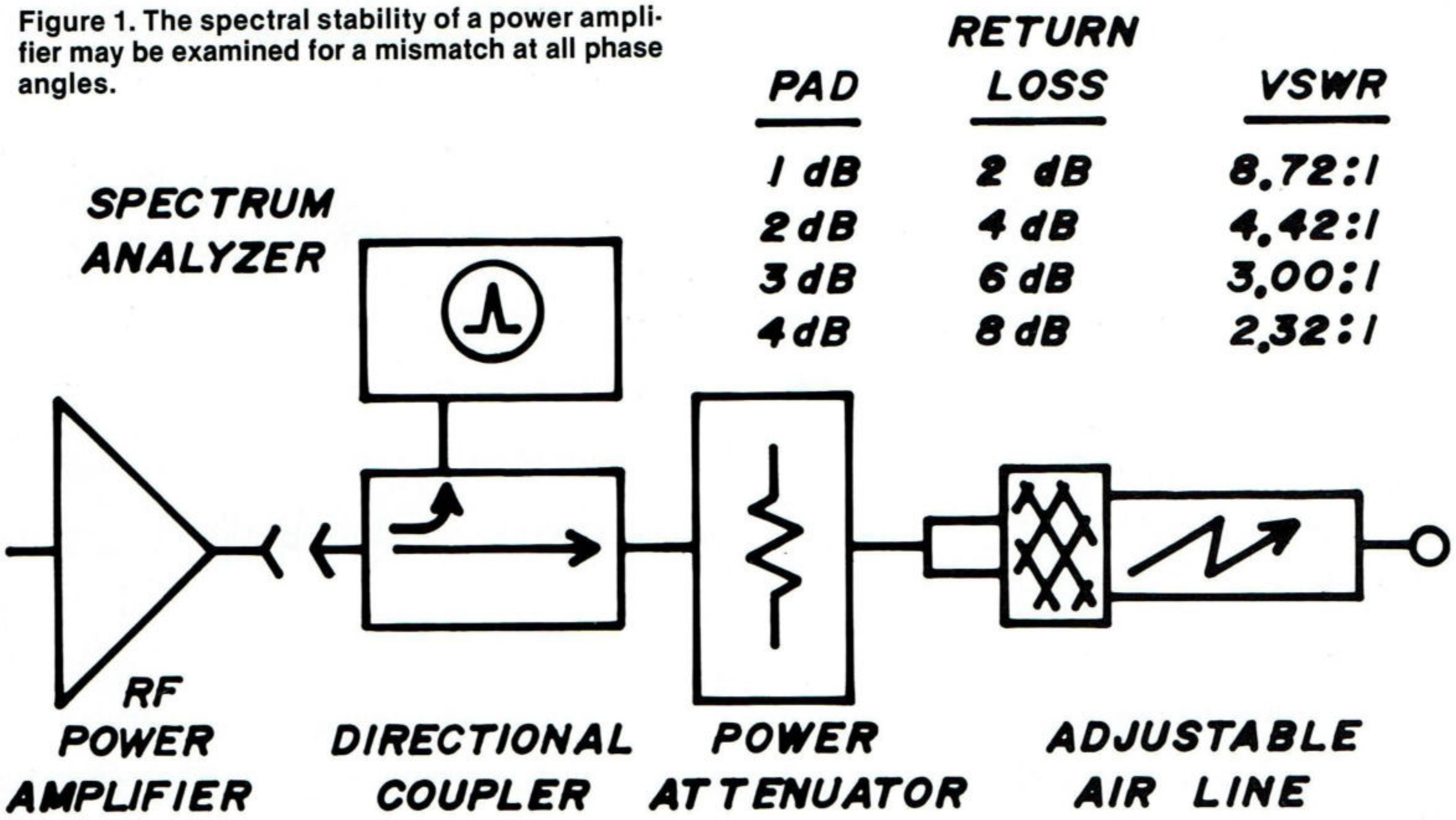

Figure 1. The spectral stability of a power amplifier may be examined for a mismatch at all phase angles.

Examination of the above equation shows two zeros in the numerator corresponding to two series resonances. A parallel resonance occurs in the denominator when

$$\omega(L_1 + L_2) = \frac{2}{\omega C} \ , \qquad (3)$$

where $C_1 = C_2 = C$ and assuming a ganged dual section or butterfly variable capacitor. The above equation may be rewritten as

$$XC = \frac{XL_1 + XL_2}{2}$$

where $XL_1 = \omega L_1$, $XL_2 = \omega L_2$ and $X_C = \frac{1}{\omega C}$.

At any given frequency, the locus of impedance points plotted on a Smith Chart as the capacitor is varied will be a circle similar to that achieved using a variable length transmission line. If an attenuator is not used, the points will be entirely imaginary (R = 0). If an attenuator is used, the value of the real and imaginary parts of the input impedance may simply be read from the chart. When properly designed, as the capacitance is increased, the locus travels from a short circuit (when $XL_1 = X_C$) (Figure 3) to an inductive

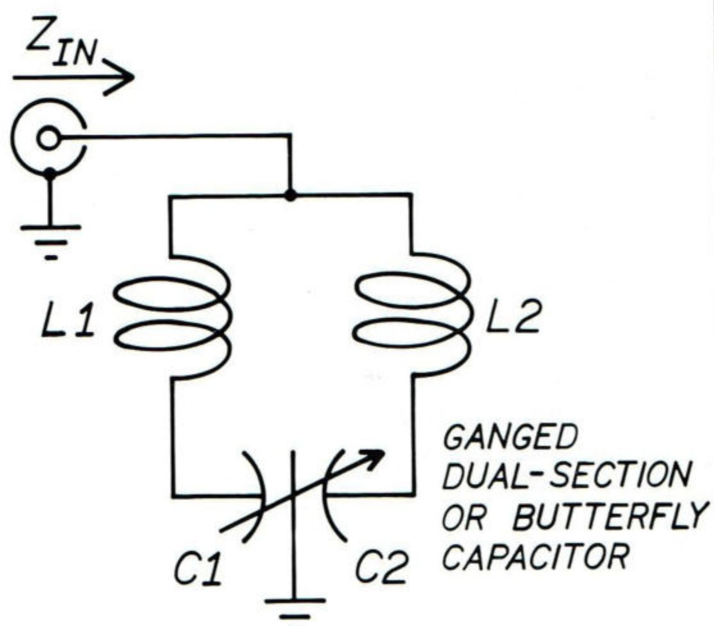

Figure 2. The lumped-constant line stretcher is formed by two series circuits which combine for a parallel combination.

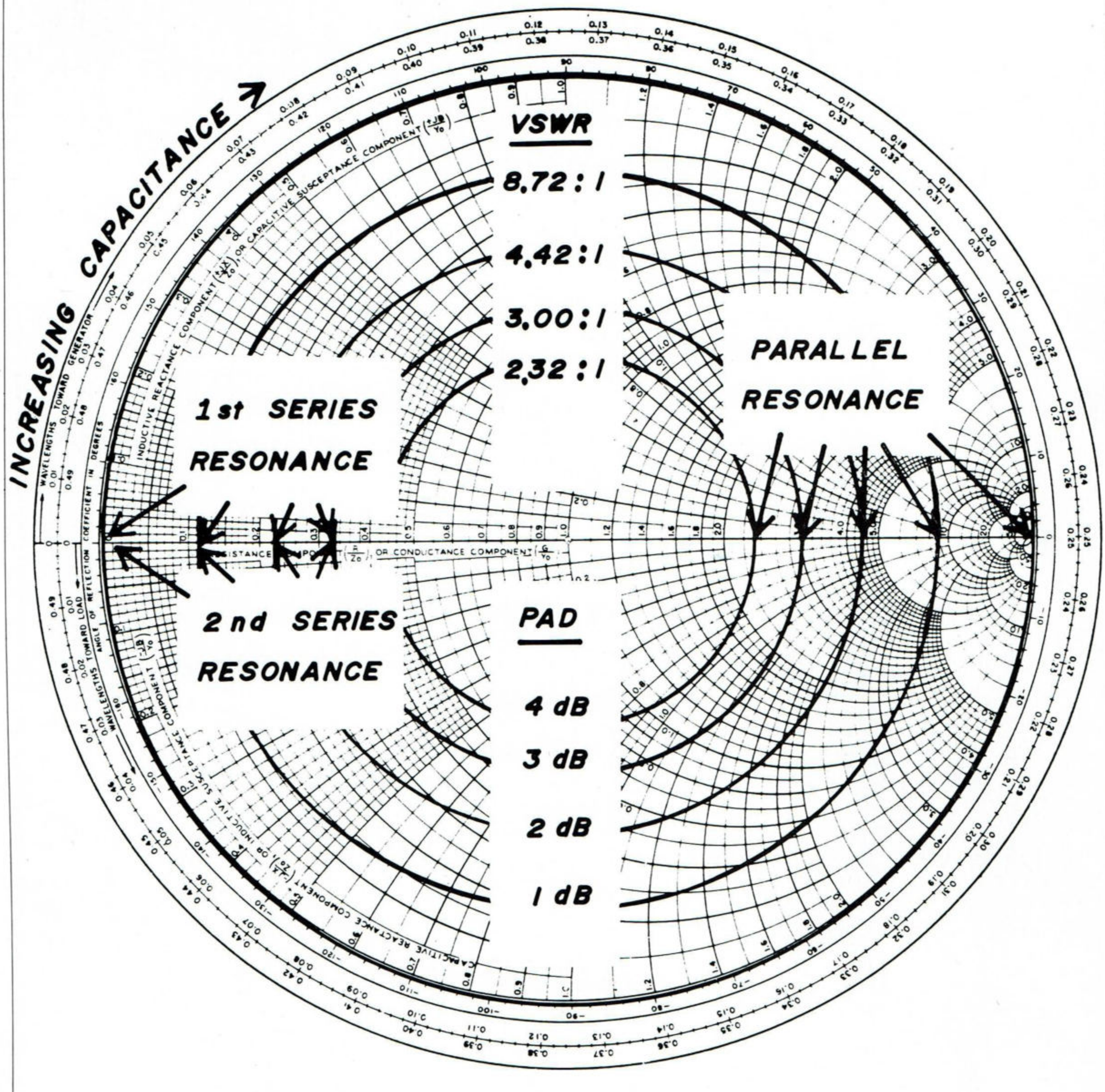

Figure 3. As the variable capacitor is meshed, the locii of input impedance points forms a clockwise circle of constant VSWR covering all phase angles.

reactance, then through parallel resonance to a capacitive reactance. Finally the locus passes through the second series resonance (when $XL_2 = X_C$) near maximum capacitance.

By properly dictating the end points of the locii at the series resonances, the parallel resonance will occur somewhere between them.

For design purposes, it is necessary to establish the frequency bandwidth over which the lumped-constant variable line has to work. Next the ganged dual-section or butterfly capacitor selected must have a high breakdown voltage and a very high Q. Any dissipative loss in the coil or capacitor will be evidenced by a non-circular response on the Smith Chart. Before any calculations for the inductors are made, the minimum and maximum capacitance should be measured. It is also necessary that the capacitor does not have a self resonance anywhere in the frequency band of interest.

Inductor L_1 is calculated using the maximum capacitance at the lowest operating frequency for series resonance.

$$L_1 = \frac{1}{4\pi^2 (F_{low})^2 C_{max}} \tag{4}$$

The second inductor L_2 is calculated using the minimum variable capacitance at the highest operating frequency.

$$L_2 = \frac{1}{4\pi^2 (F_{high})^2 C_{min}} \tag{5}$$

The ratio of inductance L1/L2 must be less than unity

$$\frac{L1}{L2} = \left(\frac{F_{high}}{F_{low}}\right)^2 \left(\frac{C_{min}}{C_{max}}\right), \tag{6}$$

which reduces to

$$\left(\frac{F_{high}}{F_{low}}\right)^2 < \left(\frac{C_{max}}{C_{min}}\right). \tag{7}$$

If the inductors are equal, then parallel resonance will occur at the same time as series resonance both at the highest frequency (C_{min}) and at the lowest frequency (C_{max}).

If the ratio of L1/L2 is greater than unity, parallel resonance will not occur within the frequency range F_{low} to F_{high}.

From equation 7, the operating range is limited by the square root of the capacitance ratio. It should be remembered that the input impedance will vary faster when a wider frequency range is chosen. Thus to insure a more gradual change in impedance as the capacitor is rotated, the frequency range is usually limited only to the band of interest.

VHF Example

As an example calculation, a variable line was designed to operate over the two-way radio band, 150 to 175 MHz. A dual variable capacitor was chosen with a minimum capacitance of 7.5 pF and a maximum of 50 pF. We shall limit the range of capacitance to $C_{min} = 10$ pF and $C_{max} = 45$ pF to account for parasitic capacitance and to operate slightly away from the capacitor stops.

$$L_1 = \frac{1}{4\,\pi^2\,(F_{low})^2\,C_{max}} = \frac{1}{4\,\pi^2\,(150\text{MHz})^2\,(45\text{pF})} = 25\text{ nH}$$

$$L_2 = \frac{1}{4\,\pi^2\,(F_{high})^2\,C_{min}} = \frac{1}{4\,\pi^2\,(175\text{ MHz})^2\,(10\text{pF})} = 83\text{ nH}$$

Very low values of inductance may be simply short lengths of wire or flat copper strips. The exact value is determined by adjusting for series resonance at each end of the capacitor travel.

The input impedance may be quickly examined at band edges. At 150 MHz the first series resonance occurs at C_{max} = 45pF by the above design. At the second series resonance, the variable capacitor resonates with the other inductor L2.

$$XC = XL_2 = 2\pi fL_2 = 2\,\pi\,(150\text{ MHz})(83\text{ nH}) = 78\text{ ohms}$$

$$C = \frac{1}{2\pi f\,X_c} = \frac{1}{2\pi\,(150\text{MHz}\,(78\text{ ohm})} = 13.6\text{ pF}$$

A parallel resonance will occur between the two series resonances when all of the components are taken into account.

$$XC = \frac{XL_1 + XL_2}{2} = \frac{2\pi\,f\,(L_1 + L_2)}{2}$$

$$= \pi(150\text{MHz})\,(25\text{nH} + 83\text{nH}) = 50.9\text{ ohm}$$

$$C = \frac{1}{2\pi fXC} = \frac{1}{2\pi\,(150\text{MHz})(78\text{ ohm})} = 20.8\text{ pF}$$

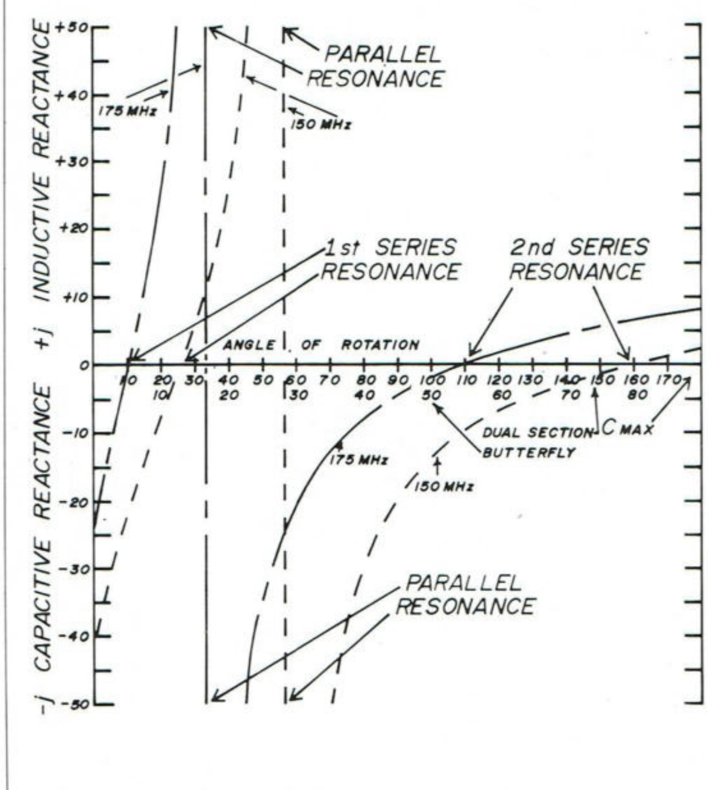

Figure 4.

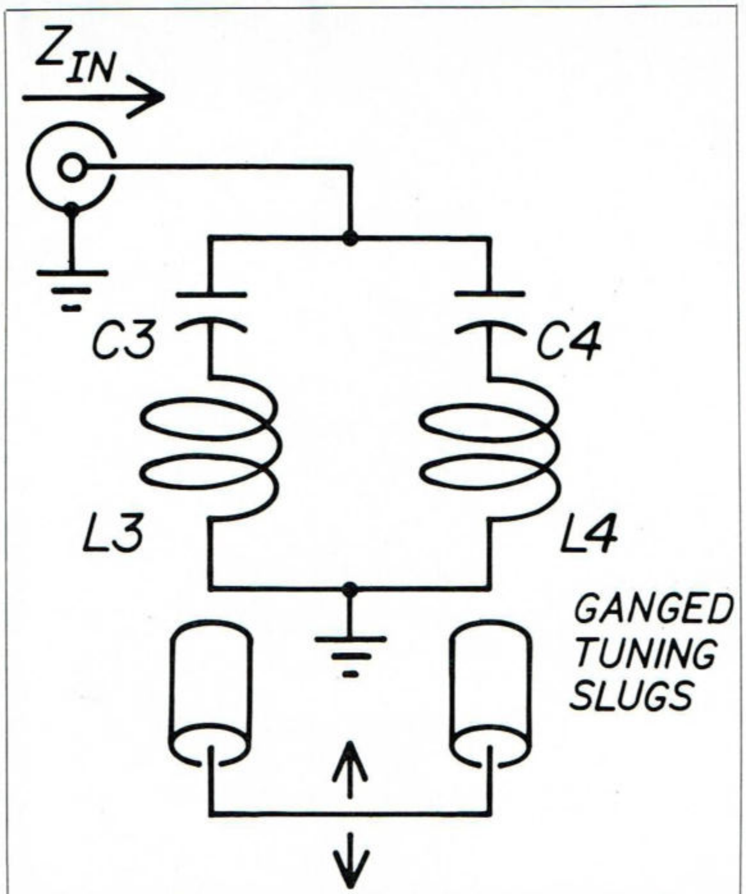

Figure 5. The lumped-constant adjustable line simulator may also be formed using a permeability tuner.

At the high end of the band (175 MHz) the following conditions are present:

First Series Resonance	C = 33 pF
Parallel Resonance	C = 15.3 pF
Second Resonance	C = 10 pF

The input impedance is plotted as a function of capcitor rotation for the lowest and highest operating frequency in Figure 4. Rotation is shown both for a semi-circular (180°) and a butterfly (90°) capacitor. A gear reduction is typically employed with a calibrated dial. The equation for the capacitor is assumed to be linear

$$C = [(\theta/180°)(C_{max} - C_{min})] + C_{min}$$

where

θ = angular rotation in degrees from fully open
C_{max} = 50 pF
C_{min} = 7.5 pF

The allowable RF power input to this type of device is dependent on the breakdown voltage of the capacitor. For the above design a 500V breakdown capacitor was used and 150 Watts of RF power was applied without any adverse effects.

Variable Inductance Line Stretcher

The variable may be switched from the capacitor to the inductor (Figure 5). A slug formed from ferrite, brass, copper, or aluminum may be mechanically positioned within two identical inductors to vary the inductance. The fixed capacitors, C3 and C4, are computed in a similar manner as above. The conductive metallic core acts as a single shorted turn to decrease the inductance with increased penetration. The powdered iron or ferrite core has the opposite effect and increases the inductance as it penetrates the coil. The Q of the coil is not appreciably lowered when using the brass slug provided the slug has a clean surface or is silver plated. The use of the powdered iron or ferrite core will raise the Q of the coil provided the material has been selected for the frequency range in use. Ferrite and powdered iron are typically usable up to 200 MHz.

Variable Inductor Example

When a slug having a permeability of μ is inserted into an air-core inductance L_{air}, the final inductance becomes $\mu L_{air} = L_{core}$. Thus L_{core} and L_{air} are the maximum and minimum values of inductance.

If the minimum and maximum of the matched coils are chosen for example to be $L_{max} = L_{core} = 83$ nH and $L_{min} = L_{air} = 25$ nH, the values of capacitance may be then calculated.

$$\mu = \frac{L_{core}}{L_{air}} = \frac{83\text{ nH}}{25\text{ nH}} = 3.3\text{, ferrite}$$

$$C_3 = \frac{1}{4\pi^2 (F_{low})^2 L_{max}}$$

$$C_4 = \frac{1}{4\pi^2 (F_{high})^2 L_{min}}$$

For the frequency range of 150 to 174 MHz, $C_3 = 13.56$ pF and $C_4 = 33.08$ pF. Parallel resonance will occur when

$$2\omega L = \frac{1}{\omega}\left(\frac{1}{C_3} + \frac{1}{C_4}\right)$$

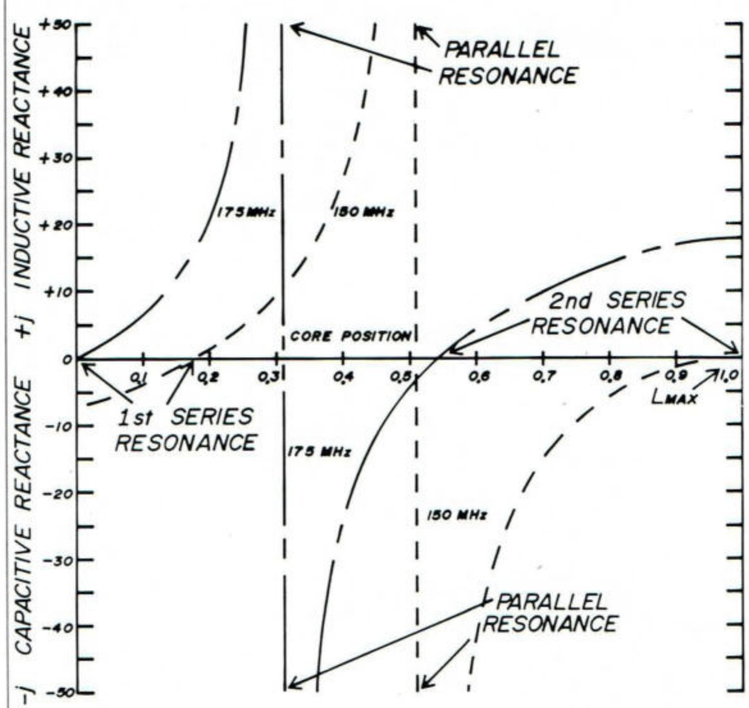

Figure 6. The input for the variable inductor is similar to the previous case as the ferrite slug is inserted into the coil.

At the low frequency of 150 MHz the value of each inductor will be

$$L = \frac{C_3 + C_4}{2\omega^2 C_3 C_4} = 58.5 \text{ nH}$$

for parallel resonance. The value of each inductor will be 43 nH for parallel resonance at 175 MHz. This is plotted in Figure 6. The abscissa is plotted as linear travel for the position of a ferrite slug into a cylindrical, linearly-wound coil whose dimensions equal those of the core being used. It represents the fraction of the core inside the coil.

Conclusion

To determine the stability of an RF power amplifier, oscillator, or transmitter under harsh conditions, a variable line and fixed attenuator are used to simulate a given VSWR at all phase angles. Below 200 MHz a half-wave adjustable line is cumbersome. This article has described a lumped-constant line stretcher using either variable capacitors or inductors.

The use of moveable slugs eliminates mechanical wear at the electrical grounding point present on the capacitor rotor. For automated testing of production transistors or amplifiers, a frictionless device is necessary.

Today there are few manufacturers still fabricating dual section or butterfly variable capacitors because their use was primarily in electron tube amplifiers.

Reference

1. R.K. Blocksome, "A Binary Stepped Transmission Line," *r.f. design,* July/August 1982, pp. 22-29.