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Modified Coaxial Cable Makes Components and Test Circuits

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This practical article describes coaxial components, including the theory and equivalent circuits for the modified coaxial cable, with simulated behavior and measured data

In the lab, coaxial cable is most often used to connect RF components. Yet, it is surprising that many engineers don't realize that the coaxial cable itself can be built into an RF component. Physically modifying a coaxial cable can alter its RF behavior in a constructive way (see Figure 1). Understanding how these modifications change the RF behavior can enable new, practical lab applications without the cost or the wait for commercial components. This paper examines the effect of modifying a simple RF coaxial cable. Experimental measurements are made on a modified coaxial cable whose center conductor is offset (i.e., made eccentric) and which has a slot cut in the shield. Describing these modifications in terms of an equivalent circuit clarifies the RF changes and opens up new applications.

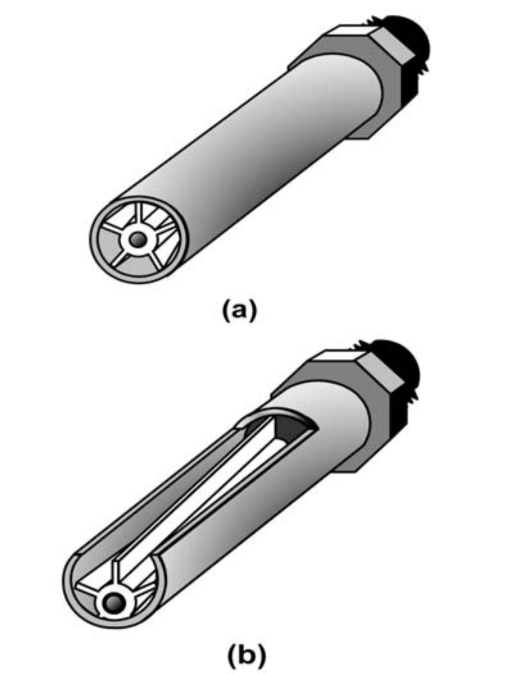

Figure 1 · (a) Cross-section of a typical coaxial cable. (b) The same cable after slotting the outer conductor and offsetting the inner conductor.

Coaxial Theory (in Brief)

In normal coaxial operation, energy propagates according to the transverse electromagnetic (TEM) mode. Modifying the cable induces other, higher-order traveling-wave modes [1]. Moding is generally an unwanted effect and difficult to predict. Exact mathematical solution of the cutoff wavelength for higher-order traveling-wave modes is difficult. The solution at the boundary conditions involves Bessel functions inserted into transcendental equations. The slot and eccentricity of the modified cable causes the fields to bend and the Poynting vector to change direction. TEM energy transforms into radial and longitudinal components.

A coaxial line is made eccentric by offsetting the inner conductor or the outer conductor [2] so the cross-section no longer has circular symmetry. In our example, the inner conductor is shifted by gradually offsetting spline spacers inside the cable.

Some readers will recall that, in the past, a slotted coaxial line was the typical fixture used for measuring standing waves [3]. According to electromagnetic theory, a slot in the coaxial

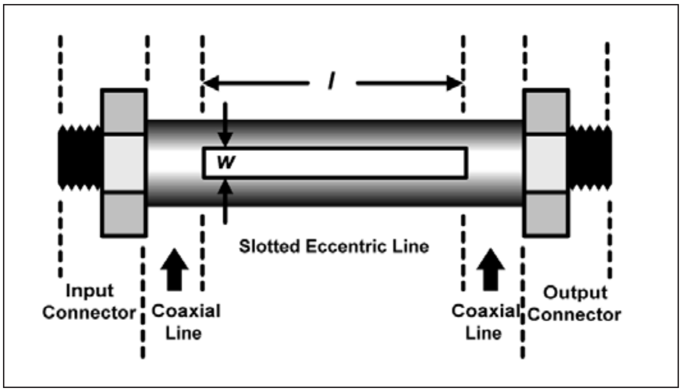

Figure 2 · Layout of a cable modified with a slot and eccentric conductors.

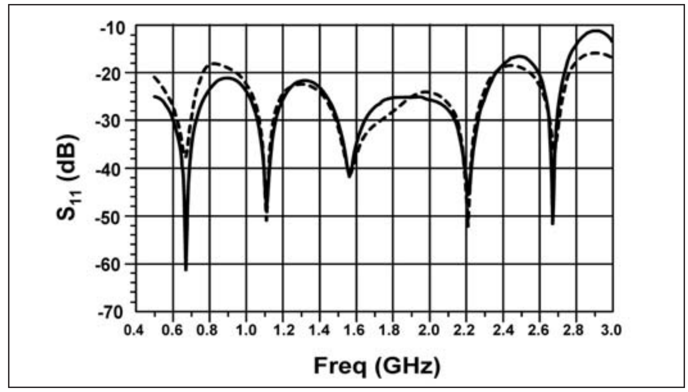

Figure 4 · Return loss of normal coaxial waveguide. Solid line is measured and dotted is simulated.

cable's outer conductor creates two modes [4, 5]. In one mode, the energy is confined primarily inside the cable. The second mode has most of the energy on the outer surface of the cable with some leakage inside. Because one mode occurs on the inner conductor and the other on the outer conductor, an equivalent circuit should include elements in both the signal and ground paths.

In general, making a coaxial line eccentric increases the line's capacitance and reduces its characteristic impedance Z_0 [6]. The distance between the center conductor and outer conductor determines when higher-order modes are excited [7]. Longitudinal components of the E-field belong to higher-order modes than the principal-order radial coaxial mode. At the slot discontinuity, power is transferred into the higher-order modes. Eccentricity splits the TEM field into even and odd modes. The even modes (TE_e and TM_e) are identical to the TEM modes in a coaxial line [8]. The odd modes (TE_o and TM_o) are unwanted and can be minimized by removing a portion of the outer conductor farthest from the inner conductor. Keep in mind that shifting the center conductor too close to the wall of the outer conductor limits the amount of power handling since high-voltage breakdown can occur in the gap between inner and outer conductor.

Altering a Coaxial Cable

To illustrate how modifying a coaxial cable affects its RF behavior, a 15-inch long coaxial cable, military specified (mil-spec) part number UT-S-390-50, was selected. The outer diameter is 0.390 in. and the inner conductor diameter is 0.150 in. with an air dielectric. Ordinarily, RF coaxial cables have a solid Teflon® dielectric. In this case of the UT-S-390-50, the inner conductor is mounted on insulating spacers or splines. The spline is a honeycomb-shaped dielectric spacer that maintains a constant distance between the inner and outer conductors. When the cable is bent, the rigidity of the spline ensures the inner conductor will not migrate towards the outer conductor over time. Since the cable's dielectric is mostly air, it has low loss. Spline coaxial cables are popular for space applications (hence the "S" designation in the part number). They withstand shock and vibration and are resistant to shrinkage and outgassing.

For this experiment, the cable was modified with a slot width w of 0.250 in. and a slot length l of 8.00 in. (see Figure 2). The center conductor is offset approximately 0.200 in. between the inner and the outer conductor. Modifications such as these can cause higher-order modes and localized moding [9]. If they propagate far, the unwanted modes can be reflected at the slot-to-coaxial transition where the slot opens in the outer conductor.

Designing a smooth transition from coaxial line to slotted eccentric line minimizes unwanted reflections. A step discontinuity exists where the outer shield is removed, represented largely as shunt capacitances. The equivalent circuit is valid for impedance measurements made at a distance large enough from the discontinuity that the higher-order modes have attenuated [10]. The coaxial connector and slot are far enough from one another so that

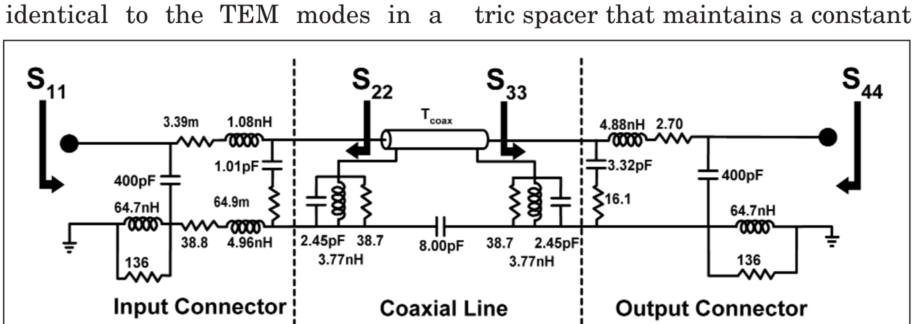

Figure 3 · Equivalent circuit of an unmodified coaxial cable.

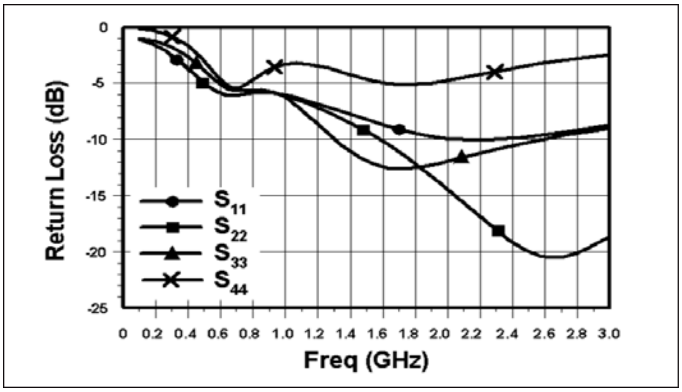

Figure 5 · Return loss of the equivalent circuit shown in Figure 2.

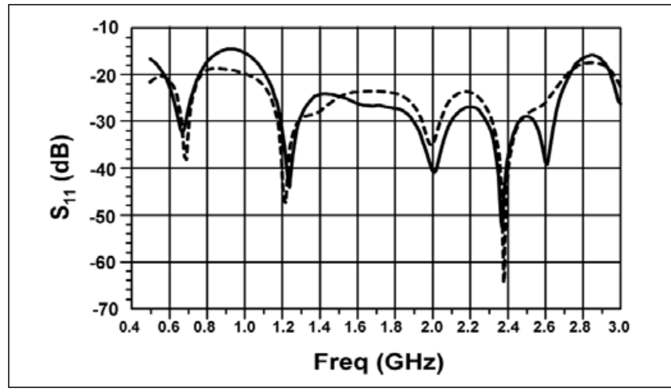

Figure 7 · Return loss of slotted, eccentric coaxial waveguide. Solid line is measured; dotted is simulated.

there is no proximity effect where the slots couple to one another's higher-order fields.

Figure 3 shows the equivalent circuit for an unmodified coaxial cable. The response of the equivalent circuit is compared to measurement in Figure 4. Equivalent circuits represent the Type-N input and output connectors. Shown in the center is the equivalent circuit for the UT-S-390-50 coaxial line. Its ground return path has an RLC circuit at each end with 8.00 pF capacitor in-between. This accounts for the reflections from the connectors. Figure 5 gives the individual performance of the connectors and coaxial line. Because they were crimped onto the ends of the cable, the connectors contribute mismatch (S_{11} and S_{44}) while the cable ports (S_{22} and S_{33}) are closer to 50-ohm characteristic impedance.

Figure 6 shows the equivalent circuit of the slotted, eccentric cable. It includes a short section of coaxial line between each connector and the slotted, eccentric line. Its response (see Figure 7) can be compared to the response of normal coaxial line (shown in Figure 4). The equivalent circuit in Figure 6 shows larger capacitance in the ground path. Also, coupling and radiation through the slot are represented by a large shunt RC between inner and outer conductors. In the next section is shown how this coupling can be used to build RF components.

Applications of the Modified Line

Two applications for the slotted, eccentric cables are directional couplers and tunable filters. In Figure 8, two slotted, eccentric lines are coupled by a common slot in their outer conductors [11]. The amount of inductive coupling is determined by the width of the slot while the capacitive coupling depends on the spacing between the center conductors. Proper design of the discontinuity at the entrance and exit to the slot will improve the coupler's directivity by maintaining 50-ohm impedance throughout the length of the line. Making the center conductor eccentric is much simpler than changing the diameter of either the inner or outer conductors [12]. The coupling factor K between ports 1 and 3 is

$$K = \frac{1}{2}\left(k - \frac{1}{k}\right)\sin \beta l \qquad (1)$$

where: k = constant determined by slot width and spacing between conductors; $\beta = 2\pi/\lambda$; and l = the length of the slot. For maximum power transfer, $l = \lambda/4$, $3\lambda/4$, $5\lambda/4$, etc. (odd multiple of $\lambda/4$).

Another application is as an adjustable, tunable filter (see Figure 9). Rotating a sleeve wrapped around the outer conductor of a slotted, eccentric line tunes the slot of the outer conductor [13]. The opening in the tuning sleeve eliminates capacitance and ground inductance while the shield section more resembles a conventional coaxial line. Moving the sleeve's slot along the length of the cable tunes it to a particular frequency.

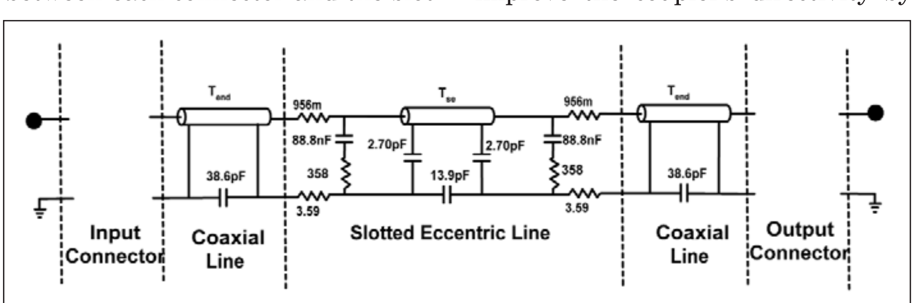

Figure 6 · Equivalent circuit of slotted, eccentric cable.

Summary

This paper examines how modifying a coaxial cable enables its use for other components in an RF lab such as a tunable filter or a directional coupler. As an example, a slot is cut in the cable's outer shield and the coaxial center conductor is offset.

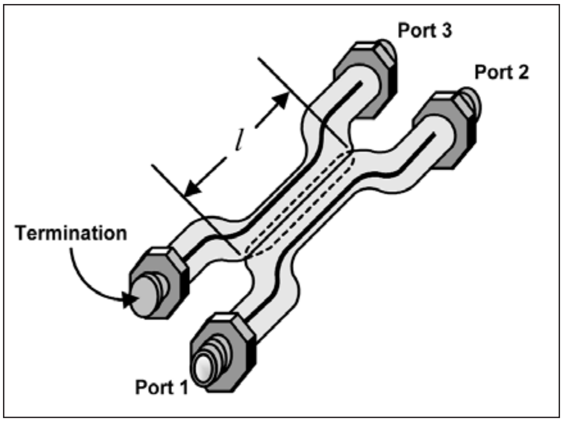

Figure 8 · λ/4 directional coupler. The length of the coupling slot is *l*.

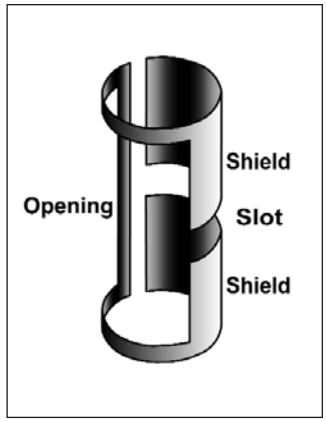

Figure 9 · Tuning sleeve construction.

Experimental measurements made on a modified coaxial cable show the effect on the cable's RF behavior. Describing the modifications in terms of the cable's equivalent circuit highlights the effect on the RF behavior.

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