Twisted-Wire Quadrature Hybrid Directional Couplers

That title scare you off? Well, don't let it. Just read this and we'll make believers out of you.

By Reed Fisher,* W2CQH

In a previous article[1] it was shown how 3-dB directional couplers or quadrature hybrids could be used to effectively parallel two uhf amplifiers or attain circular antenna polarization. The quadrature hybrid is clearly a very useful circuit. Unfortunately, the uhf strip-line models cannot be scaled down to the high-frequency amateur bands since their dimensions could become prohibitively large. This article shows how compact, low-cost, lumped-element, quadrature hybrids can be easily constructed for use in the hf amateur bands.

Theory

Figs. 1 and 2 show, respectively, the circuit diagram and photograph of a twisted-wire hybrid suitable for use in the 40-meter band. The coupling transformer consists of two insulated copper wires tightly twisted together, thereby forming a bifilar pair. The pair is then wound around a small ferrite toroid (at vhf an air-core solenoid will be suitable). The transformer is then connected to the four BNC connectors along with two molded mica capacitors. The circuit is then placed in a suitable metal enclosure. This four-port (connector) circuit will function as a hybrid or directional coupler if constructed properly.

What should a hybrid do? Let's reiterate the hybrid functions given in Ref. 1. When the hybrid is driven by a generator and connected to matched (Z_0) loads, as shown in Fig. 1, it should perform as follows:

1) There is transfer (coupling) of power from port 1 to port 2.

2) There is transfer of power from port 1 to port 4.

3) There is *no* transfer of power from port 1 to port 3.

4)There is *no* reflected power back out of port 1 (VSWR = 1:1).

5) The voltage V_2 and V_4 differ in phase by 90 degrees, hence the name quadrature hybrid.

Conditions 3, 4 and 5, above, are *theoretically independent* of frequency. Thus, for certain applications, the hybrid can be used on more than one amateur band. The term *coupling,* which *is* frequency dependent, refers to the ratio of power leaving port 2 (or port 4) to that entering port 1.

$$\text{Coupling (dB)} = -10 \log_{10} \frac{\text{Power leaving port 2 (or 4)}}{\text{Power entering port 1}}$$

Fig. 3 shows the coupling characteristics of the twisted-wire hybrid. Note that at frequency f_0 the coupling is 3 dB, meaning that equal power emerges from ports 2 and 4. Thus the hybrid, when operated near f_0, functions as a *matched power splitter*. This means that the loads connected to ports 2 and 4 not only receive equal power, but also see a matched (Z_0) generator. Therefore, when the hybrid is inserted into any transmission line, it will split the power into two parts without introducing any impedance mismatch.

Hybrid Design

A twisted-wire hybrid may be designed by considering Fig. 4, which shows the coupling transformer and capacitors removed from the baseplate and reconnected in two ways. In Fig. 4A, the connections are arranged such that the transformer "looks like" a simple inductor. The inductance, L, measured at points x-x, is found by connecting the circuits to an impedance bridge or using the grid-dipper technique described in the *Handbook.*[2] The capacitors are, of course, shorted out and can be removed for this measurement.

In Fig. 4B the connections are rearranged such that the transformer interwinding capacitance and external capacitors together "look like" a single capacitor. The capacitance C, at points y-y, can be measured by a 60-Hz capacitance bridge.

When reconnected as shown in Fig. 1,

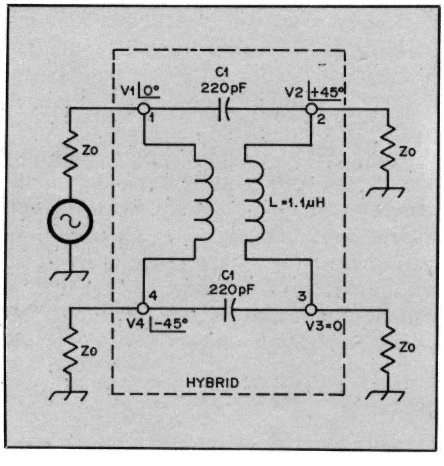

Fig. 1 — 7-MHz hybrid circuit.

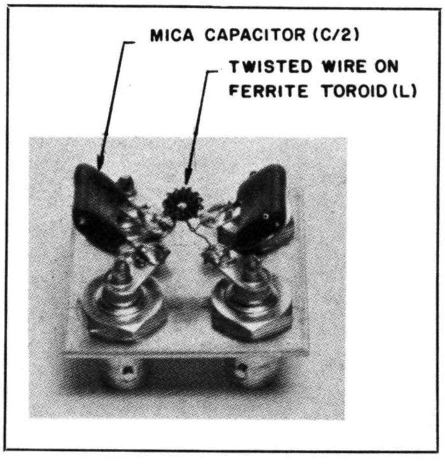

Fig. 2 — The 7-MHz hybrid.

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[1]References appear on page 23.

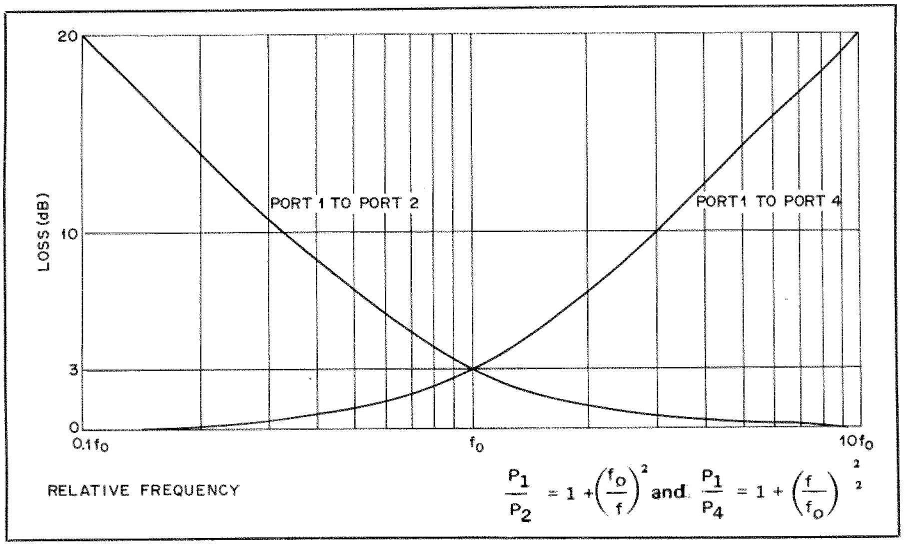

Fig. 3 — Quadrature hybrid theoretical insertion loss versus frequency.

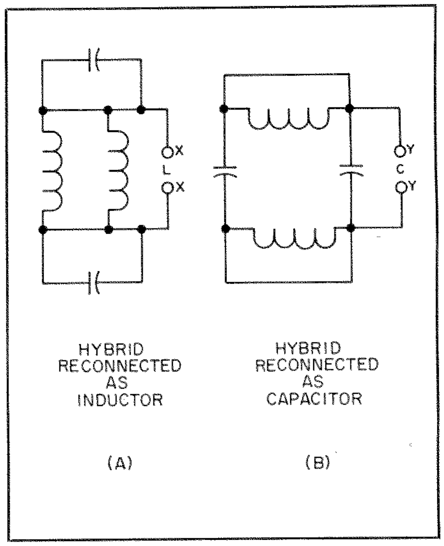

Fig. 4 — Measurement connections.

the hybrid will perform properly when

$$Z_o = \sqrt{\frac{L}{C}} \qquad \text{(Eq. 1)}$$

Equal power division (3 dB) between ports 2 and 4 will occur at a frequency f_o where

$$2\pi f_o L = Z_o \qquad \text{(Eq. 2)}$$

and

$$\frac{1}{2\pi f_o C} = Z_o \qquad \text{(Eq. 3)}$$

Eq. 2 simply means that the reactance of L (as measured per Fig. 4A) must equal Z_o (the desired load impedance) at the "3-dB" frequency f_o shown in Fig. 3. Eq. 3 means that the reactance of C (as measured per Fig. 4B) must equal Z_o at frequency f_o. The values of L and C necessary to obtain the required reactance also can be found by consulting a reactance chart.[3]

Example of Hybrid Design

Suppose we want to design the 7-MHz hybrid shown in Fig. 2. Then

$$Z_o = 50 \text{ ohms} \qquad \text{(Eq. 4)}$$

and

$$f_o = 7 \text{ MHz} \qquad \text{(Eq. 5)}$$

A reactance chart shows that to satisfy Eqs. 2 and 3,

$$L = 1.1\ \mu H \qquad \text{(Eq. 6)}$$

and

$$C = 450 \text{ pF} \qquad \text{(Eq. 7)}$$

The transformer is constructed by taking two strands of AWG No. 30 Formex magnet wire and twisting them tightly together to form a bifilar pair having approximately 10 twists per inch (the wire size and twist are not critical). It was found that when 12 turns of this pair were wound on a small ferrite toroid,* the inductance (measured as per Fig. 4B) was nearly 1.1 μH.

The measured capacitance between bifilar wire pairs was found to be 12 pF (typically 35 pF/foot). Therefore, the end terminal capacitors (C1 in Fig. 1) must each be

$$C1 = \frac{450 - 12}{2} = 219 \text{ pF} \qquad \text{(Eq. 8)}$$

When assembled as shown in Fig. 2, the hybrid functioned correctly the first time without requiring any trimming of inductance or capacitance.

Hybrid Applications

Fig. 5 suggests some applications for the quadrature hybrid. In Fig. 5B, two receivers are fed from a common antenna or vhf converter. If the 3-dB (f_o) frequency of the hybrid is near the output frequency of the preamplifier or converter, each receiver will receive an equal amount of power. If each receiver input impedance is Z_o, then no power will be lost in the Z_o termination connected to port 3 of the hybrid.

In Fig. 5B, the hybrid is used to obtain an *unequal* split in generator power. The generator frequency is at one-third the hybrid 3-dB frequency, f_o. Therefore, as indicated by Fig. 3, the power arriving at the load connected to port 4 of the hybrid will be attenuated by 0.5 dB, while the power emerging from port 2 will be 10 dB down. In this case, the hybrid is functioning as a directional coupler. If the detector and load impedances are near the value of Z_o, no power will be dissipated in the Z_o termination connected to port 3; also, the impedance looking into port 1 will be Z_o.

*[Editor's Note: The toroid was part no. CF-101 Q2 made by Indiana General Corporation, Keasby, NJ. Outside diameter of toroid was 0.230 inch, thickness was 0.60 inch, and permeability approximately 100.]

Fig. 5C shows the parallel operation of two amplifiers, a particularly useful application first mentioned in Ref. 1. This connection provides excellent amplifier isolation and virtually eliminates interaction between them, thus "taming" most tuned transistor amplifiers. The circuit is unique in that, if the amplifiers are identical, then the impedance seen looking into port 1 of the first hybrid and port 2 of the second hybrid will always have the value Z_o regardless of the amplifiers' input and output impedances.

Fig. 5D shows how an impedance-matched spdt switch can be constructed from two hybrids and two spst switches. When the spst switches (which can be semiconductor diodes) are open, all of the power from the generator will flow into load no. 2. When the switches are closed, all of the generator power will be diverted to load no. 1. In either case, the generator and both loads will always see an impedance of Z_o.

In Fig. 5E, the switches have been replaced by two identical band-pass filters. For frequencies that fall in the passband of the filters, all power from the generator will flow into load no. 2. However, for frequencies outside the filter passband the generator power will be diverted into load no. 1. As before, the generator and both loads always see impedance Z_o.

Hybrid Limitations

Fig. 3 implies that the twisted-wire hybrid is principally a one-band device since the coupling remains near 3 dB over a relatively narrow frequency region. A

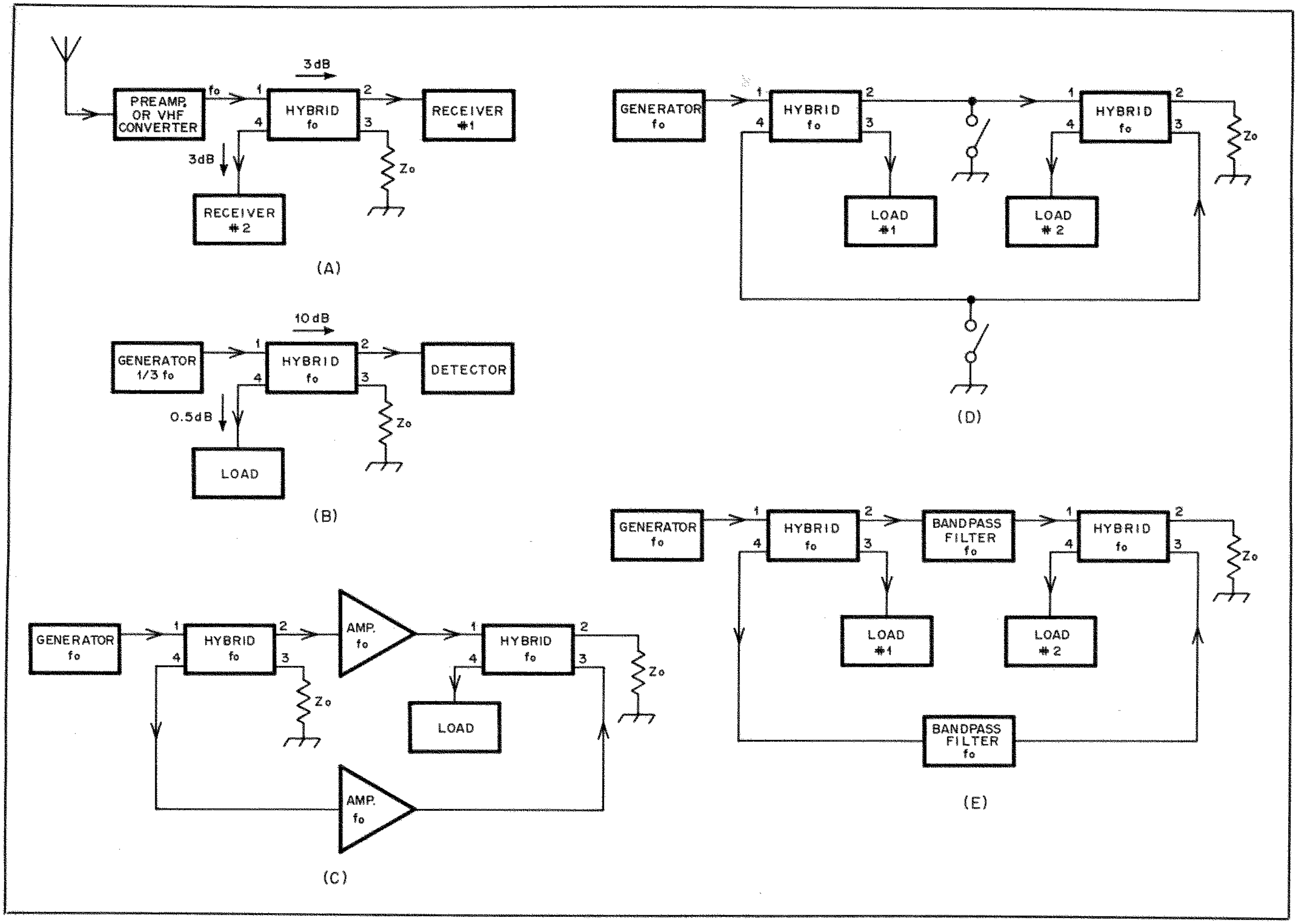

Fig. 5 — Various hybrid applications.

method of cascading two couplers to obtain wider bandwidth has been described in the literature.[4]

The upper frequency of operation is limited by the minimum value of capacitance C (Fig. 4B), which is the capacitance between turns of the bifilar winding. These hybrids have been made to operate successfully at 900 MHz.

Power-handling capability is limited by ferrite-core saturation and/or insulation breakdown in the bifilar section. The hybrid shown in Fig. 2 should be able to handle at least 10 watts. Higher power hybrids can be constructed by employing not only wire with thicker insulation, but also larger ferrite cores. It may be profitable to experiment with an air-core transformer by simply winding the bifilar pair into a solenoid. However, the design equations hold only for a "lumped network"; therefore, the length of the bifilar pair should not exceed perhaps one-tenth wavelength.

References

[1] Fisher and Turrin, "UHF Directional Couplers," *QST*, September, 1970.
[2] *The Radio Amateur's Handbook*, 1971 edition, p. 541.
[3] *The Radio Amateur's Handbook*, 1971 edition, p. 35.
[4] Fisher, "Broadband Twisted-Wire Quadrature Hybrids," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-21, No. 5, May, 1973, pp. 355-357.