Band-Splitting Filter

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A constant-resistance filter capable of dividing a very wide band into two subbands is described. It can handle one octave in the millimeter region with only 1.5 db insertion loss for each subband. The splitting transition takes place in a very narrow band (160 mc). Two of its components are important devices: an elbow and a hybrid junction. Both are quasi-optical and work with $TE_{01}°$ *mode in 2 inch diameter waveguide.*

I. INTRODUCTION

The long-distance waveguide communication system will handle an extremely broad band extending perhaps from 40 to 80 kmc.[1] For regeneration and amplification this band must be divided into channels around 400 mc apart. Promising filters capable of performing this channel separation have been described elsewhere,[2,3,4] but it is improbable that satisfactory filtering can be obtained if approximately 100 channel-dropping filters are to be stacked one after another. The main reasons for possible trouble are:

(a) Resonance of unwanted modes. This occurs because some of the filters are required to operate over a range of frequencies covering more than one octave.

(b) Multiple reflections. Although the reflection from each filter is small, the combined reflection of as many as 100 may become prohibitively large at discrete frequencies.

Troubles from these sources can be reduced by dividing the broad 40-kmc band into several subbands. The width of the subbands can be adjusted to accommodate a suitable number of channel-dropping filters.

This paper describes a filter capable of dividing a band in two parts. It can easily handle one octave in the millimeter region with low insertion loss because it operates with low loss mode $TE_{01}°$ mostly in 2 inch diameter waveguide.

The splitting process can be repeated as many times as necessary by cascading similar filters.

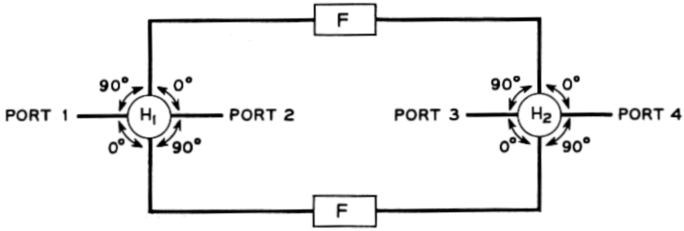

Fig. 1 — Band-splitting filter.

A band-splitting filter has been built and tested. The results are quite promising.

II. BAND-SPLITTING FILTER

The band-splitting filter is a constant-resistance filter, Fig. 1, made essentially of two identical hybrid junctions H_1 and H_2 and two identical high-pass filters F. The phase-shifts between arms of the hybrids are shown in the figure. Power entering in port 1 is divided by the hybrid H_1 into two equal parts that travel through equal electrical paths toward the high pass filters. Frequencies above that of cutoff of the filters keep on traveling and recombine with the same phase in port 4, and the opposite phase in port 3. Frequencies below that of cutoff of the filters are rejected and add in port 2 and subtract in port 1. Consequently, all the power entering in port 1 is recovered in ports 2 and 4.

What happens at frequencies where the hybrids are identical but do not divide power in equal parts? The unitary power entering in port 1 is divided by the hybrid H_1 in two parts, Γ and $1 - \Gamma$, that travel toward the filters. Due to conservation of energy the phase-shifts in the hybrids are independent of the value Γ, and the powers appearing in ports 3 and 4 (above cutoff) are

$$P_3 = 1 - 4\Gamma(1 - \Gamma), \tag{1}$$

$$P_4 = 4\Gamma(1 - \Gamma). \tag{2}$$

Power recovered in the first hybrid (below cutoff) is

$$P_1 = 1 - 4\Gamma(1 - \Gamma), \tag{3}$$

$$P_2 = 4\Gamma(1 - \Gamma). \tag{4}$$

We check immediately that if the hybrids operate ideally splitting power in halves, $\Gamma = \frac{1}{2}$ and

$$P_1 = P_3 = 0,$$

$$P_2 = P_4 = 1.$$

P_2 and P_4 given in (2) and (4) measure the recoverable power when the hybrids are not ideal. Let us plug some numbers into these expressions. For $\Gamma = 0.333 \cdots$ or $\Gamma = 0.666 \cdots$, $P_2 = P_4 = \frac{8}{9}$. In words, even at frequencies where the power division of the hybrids is as bad as two to one, the recoverable power of the band-splitting filter is as high as eight-ninths of the input power (0.5 db loss). This good behavior of the band-splitting filter, even with unequal power division in the hybrid, assures satisfactory operation over an extremely broad band.

An experimental model of a band-splitting filter operating with circular-electric mode is shown in Fig. 2, and its schematic appears in Fig. 3. It is interesting to note that we have used two elbows between the generator and the actual band-splitting filter just for "compactness."

We describe now the experimental technique used to evaluate the band-splitting filter and the results.

Most of the experimental data is presented in oscillographs that carry frequencies in abscissas and power in ordinates. The insertion loss of a device, for example, can be calculated from two oscillographs which show the transmitted powers with and without the device included in the microwave circuitry.

The wide band-sweep displayed in each oscillograph has been achieved through the use of backward wave oscillators, but we had to pay a price in that the output power of these tubes varies rapidly with frequency, and therefore the oscillographs exhibit a fine structure that makes measurement a little cumbersome.

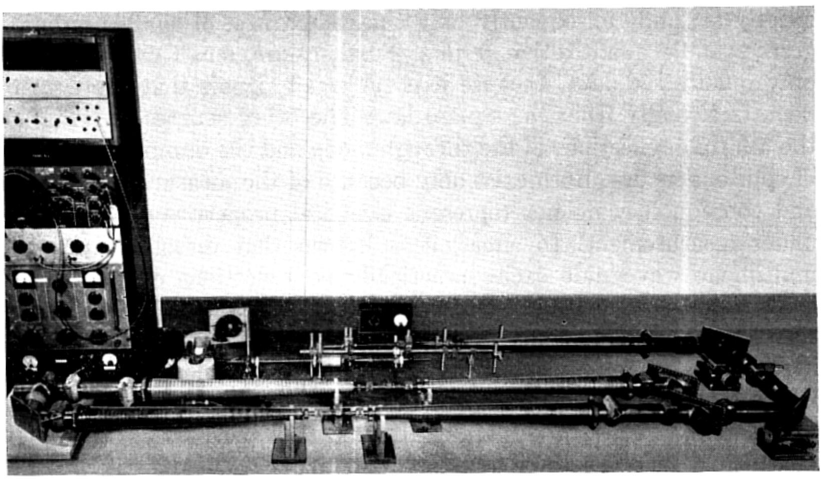

Fig. 2 — Band-splitting filter for $TE_{01}°$.

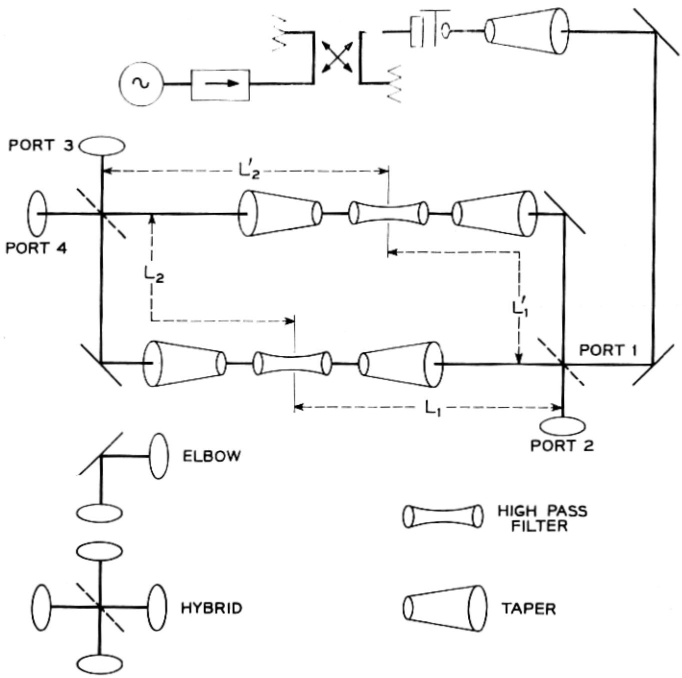

Fig. 3 — Schematic of a band-splitting filter connected to a generator.

There are several sources of errors in our measurements. One stems from the assumption that we have a square-law detector; this is not strictly so, and consequently only the comparison of similar ordinates gives reliable quantitative results. Furthermore, small ordinates yield only qualitative data, because it is for small signals that the detector departs strongly from the square law. The other sources of errors are the multiple reflections of the through mode and the damped resonances of spurious modes. Both exist only because of the measuring technique, and consequently do not represent electrical properties of the devices under measurement. In effect, it is known that discontinuities in a multimode waveguide excite practically no reflections except forward conversion. Now, in order for measurements to be made, the multimode waveguide must be connected to a generator and receiver that operate in single mode rectangular waveguides. It is in the connecting transducers where most of the reflections of the through mode take place and also where the converted modes are cut off and reflected.

Multiple reflections and damped resonances show their presence in the oscillographs as very fine periodic oscillations superimposed on the already jagged backward wave oscillator output [see, for example, Fig. 8(d)]. In transmission, where is the correct reading, at the top of this fine structure, at the bottom, or someplace in between? On one hand, admitting that the fine structure is due exclusively to multiple reflections between the input and output transducers, the correct reading is at the top because the discontinuities in the transducers act like irises located outside of the nonreflecting device being measured, and consequently these irises can only reduce the transmission, never increase it. On the other hand, admitting that the fine structure is due exclusively to resonance of spurious modes, the correct reading is half-way between the top and the bottom since the transmission can be increased or decreased with resonances.[5] A fair compromise between the two extreme readings is the average.

Now we can look at the results. The outputs of the band-splitting filter of Fig. 3 are shown in Figs. 4(a), (b) and (c), together with the reference output of the generator, Fig. 4(d).

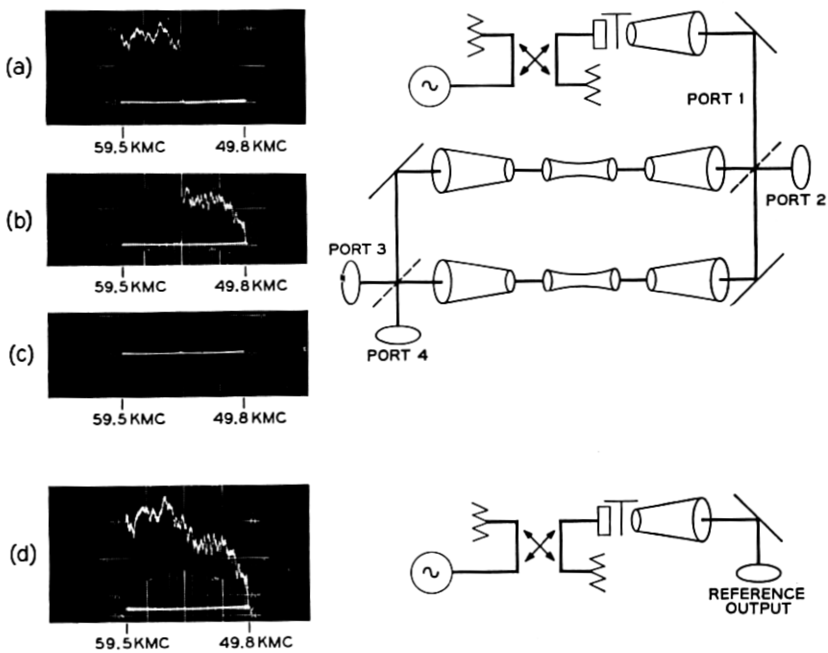

Fig. 4 — (a) Output of port 4; (b) output of port 2; (c) output of port 3 [taken with 6.0 db greater sensitivity than (a), (b) and (d)]; (d) reference output.

Far from cutoff the band-splitting filter has 1.5 ± 0.1 db insertion loss for each subband [compare Figs. 4(a), (b) and (d)]; but even as close to cutoff as 75 mc the insertion loss is increased by only 1 db. The band lost because of the splitting filter is very narrow.

It will be shown in Sections III and V that, of the 1.5 ± 0.1 db insertion loss for either subband, ~0.5 db is lost in each hybrid and ~0.2 db in each elbow. This accounts for ~1.2 db; the remaining 0.3 db must be attributed to losses in the rest of the circuitry. Any substantial reduction of losses will have to come from improvements of the hybrids.

How do we adjust the band-splitting filter? The requirement is that the power recombining at each hybrid must follow equal electrical paths. Frequencies below cutoff require path L_1 in Fig. 3 to be identical to L_1', and frequencies above cutoff must have $L_1 + L_2$ identical to $L_1' + L_2'$. The fact that the adjustment for frequencies below cutoff is independent of L_2 and L_2' suggests a two-step procedure in which the second does not alter the first:

(a) trim L_1 and L_1' for minimum power in port 1 (maximum in port 2);

(b) trim L_2 and L_2' for minimum power in port 3 (maximum in port 4).

We describe next each one of the band-splitting filter components.

III. HYBRID JUNCTION

Consider an infinite volume of metal in which two infinitely long cylindrical holes of equal diameter are bored in such a way that the axes are coplanar and normal to each other, as in Fig. 5. We thus have two cylindrical waveguides making a cross. TE_{01}° mode fed in one of the arms passes straight through the junction almost unperturbed provided the diameter of the waveguide is much larger than the free-space wavelength. The reason is that we are dealing with an almost optical problem.

Now let us include in the junction a thin plane sheet of a material to be described later. The sheet passes through the intersection of the axes of the waveguides and makes an angle of 45° with each of them. This thin layer acts as a semitransparent mirror, and TE_{01}° mode fed in one of the arms is partially transmitted straight through and partially reflected to one of the side arms. If the power division is half and half, the junction becomes a hybrid. If all the power is reflected (sheet of metal) the junction becomes an elbow, as in Fig. 6.

The semitransparent mirror can be obtained with sheets of dielectric, wire mesh, evaporated film, etc.

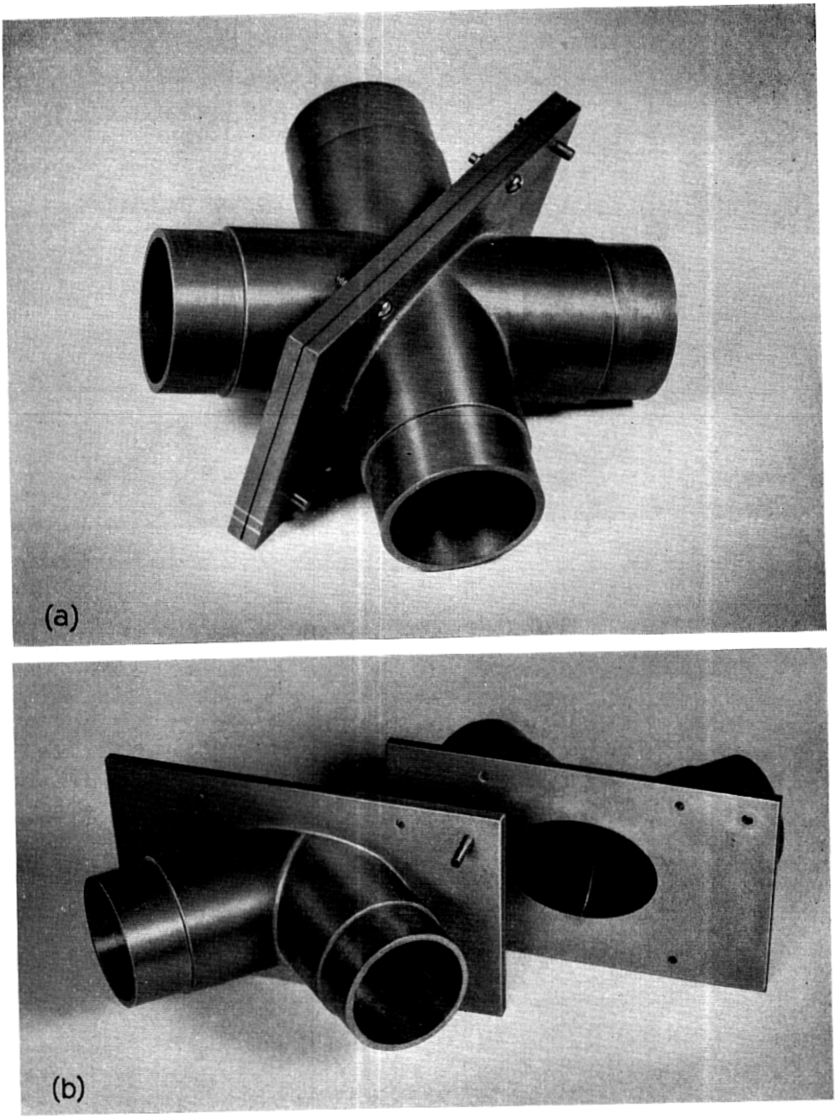

Fig. 5 — (a) TE_{01}° hybrid in 2-inch waveguide; (b) exploded view.

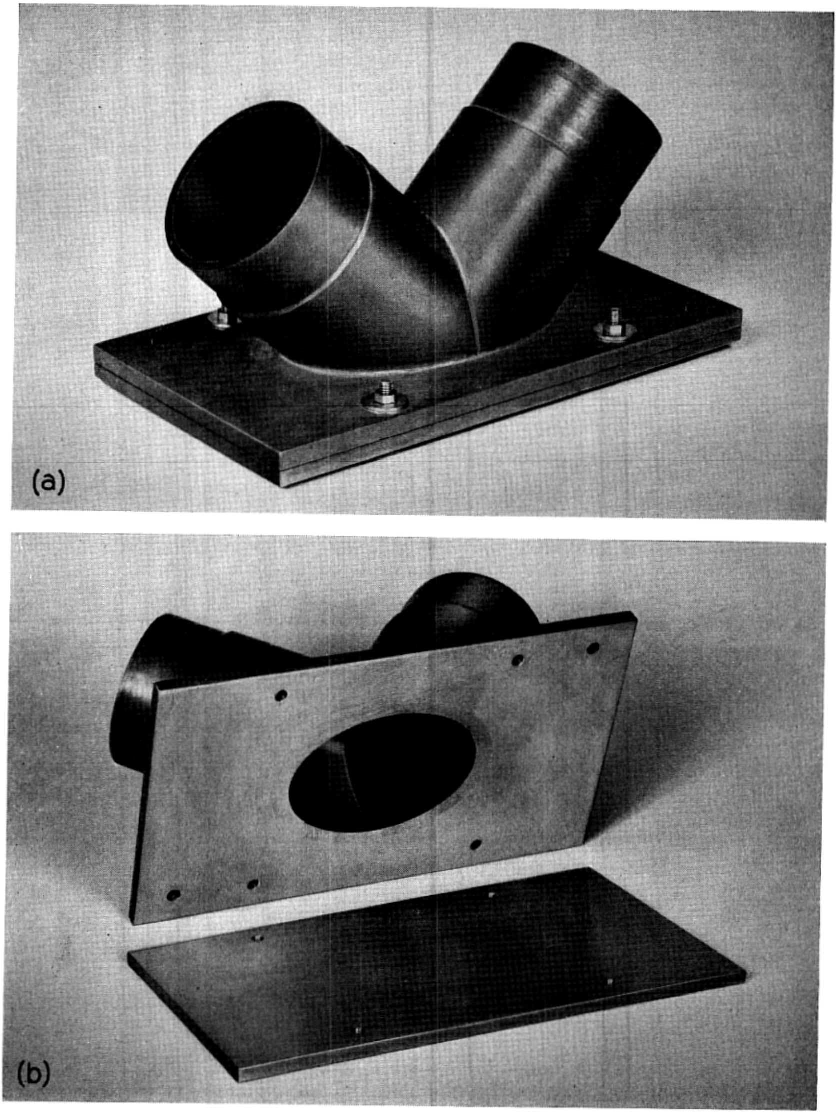

Fig. 6 — (a) $TE_{01}°$ elbow in 2-inch waveguide; (b) exploded view.

Part of the power sent through one of these hybrids is converted to unwanted modes, a good part of which could be recovered by modifying the mirror slightly. In effect, the incident mode can be considered as the superposition of an infinite number of plane wavelets all traveling almost parallel to the axis of the waveguide and each one impinging with different polarization on the semitransparent mirror. As a consequence of the polarization each wavelet has its own reflection coefficient. Mode conversion can be avoided by making the local reflection coefficients identical; this can be achieved with a nonuniform semitransparent mirror — for example, if the sheet is dielectric or wire mesh, the thickness of the dielectric or the density of the holes must be a function of the azimuth.

Let us see the experimental results. Two hybrids were assembled using glass for the semitransparent mirrors. The thicknesses were determined experimentally to provide 3 db power division in the 50 to 60 kmc band. Three sheets of glass with a total thickness of 0.018 inch were assembled into Hybrid No. 1. The other, Hybrid No. 2, was assembled with four sheets of glass with a total thickness of 0.021 inch. The power division did not change rapidly with thickness, and the two mirrors appeared to be the best combinations obtainable with the available glass sheets.

Similar measurements were made to determine the performances of both hybrids and, since the results were very similar, Fig. 7 shows only those for Hybrid No. 1. The outputs from arms 3 and 4, Figs. 7(a) and 7(b), are nearly equal, showing close to 3 db power division.

A method to check the insertion loss and the balance of the hybrid is described next. The four port hybrid is reduced to a two port structure by placing reflecting pistons in arms 3 and 4, Fig. 7(c). By adjusting the relative position of the pistons, the power transmission is maximized. With this scheme the transmitted power crosses the hybrid twice, once going toward the pistons and second, bouncing from them. Figs. 7(c) and (d) show the transmitted and reflected levels. The reference level is shown in Fig. 7(e). The two-way loss of the hybrid is approximately 1 db $\pm$ 0.1 db. The reflected power from the hybrid with the pistons is very small [see Fig. 7(d)] because it is quite similar to the power reflected in the internal mismatches of the measuring set, Fig. 7(f). This indicates first that the 1 db insertion loss is not due to reflections but rather to mode conversion; second, that over the range from 51.0 to 60.8 kmc the power division in the hybrid is frequency-insensitive, since otherwise the pistons could not tune out the reflections over this band.

The responses of Hybrids Nos. 1 and 2 from 60 to 68.4 kmc and from

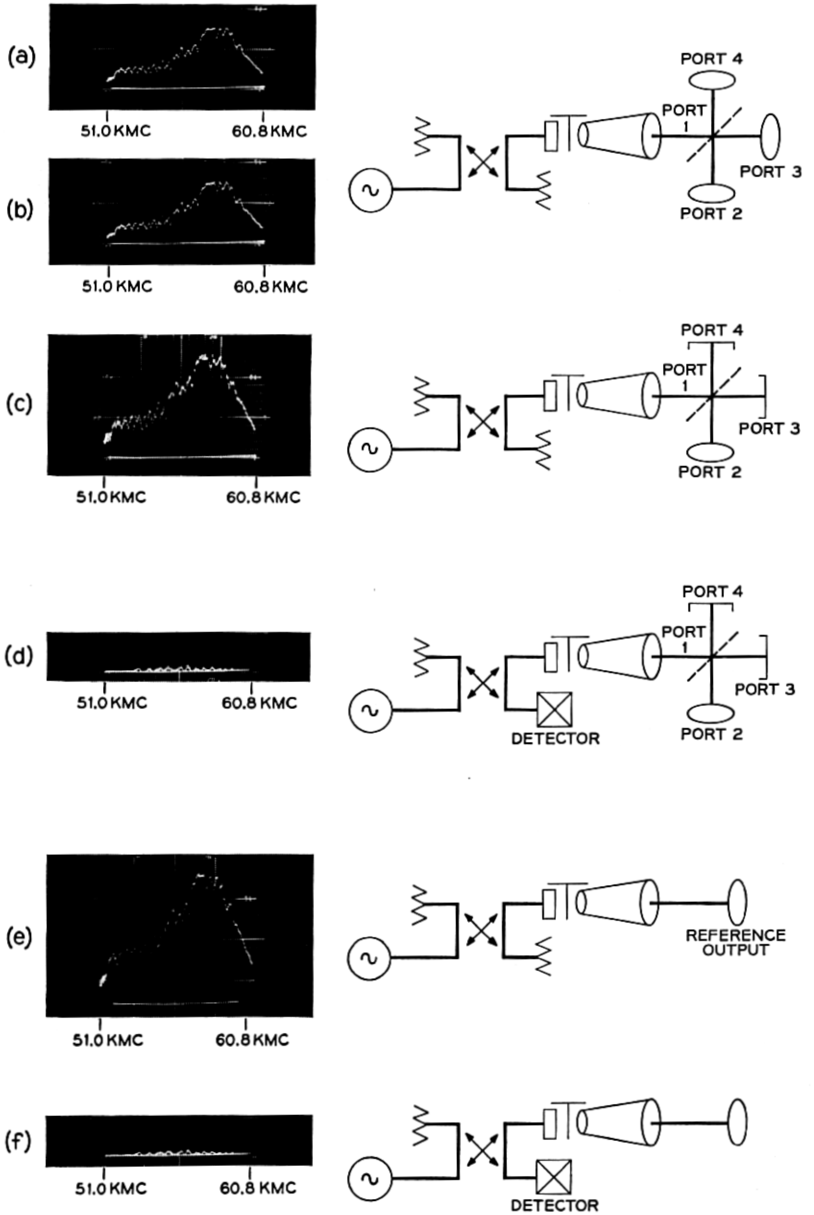

Fig. 7 — Hybrid No. 1: (a) output of port 3; (b) output of port 4; (c) output of port 2 with pistons on ports 3 and 4; (d) output of port 1 with pistons on ports 3 and 4; (e) reference output; (f) reflection from measuring set.

65.9 to 76.4 kmc are shown in Fig. 8. The outputs of arms 3 and 4, which should be equal in the ideal case of 3 db power division, have been superposed for comparison. Figs. 8(a) and 8(b) show that those outputs are very similar in Hybrid No. 1, and consequently power division has little frequency dependence. On the other hand, Figs. 8(c) and 8(d) indicate that power division in Hybrid No. 2 gets worse as the frequency increases. At the highest frequency, 76.4 kmc, the output ratio is close to two to one.

Why the dissimilar frequency behavior? The answer may be that, because of the difference in thickness of the semitransparent mirrors, the hybrids achieve the ideal 3 db power division at different frequencies, and consequently one of them is bound to behave better than the other in the range of our measurements. These hybrids are so broadband that when they were assembled to provide 3 db division in the range from 50 to 60 kmc they looked very similar, and only when they were measured at higher frequencies did the different behavior become apparent.

For the purpose of showing that other semitransparent mirrors different from glass could be adequate to build a hybrid, a copper screen was used. The copper screen is an electroformed mesh 0.0005 inch thick

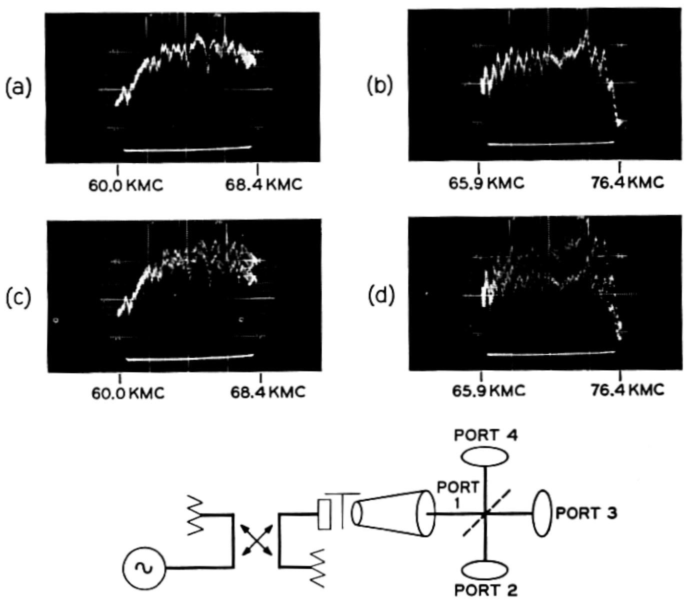

Fig. 8 — Superimposed outputs of ports 3 and 4: (a) Hybrid No. 1, 60.0 through 68.4 kmc; (b) Hybrid No. 1, 65.9 through 76.4 kmc; (c) Hybrid No. 2, 60.0 through 68.4 kmc; (d) Hybrid No. 2, 65.9 through 76.4 kmc.

with 400 square holes per square inch, with the copper separating the holes being 0.0175 inch wide.

The power division of the hybrid is 1.8 to 1, and, with more screen reflectivity, 3 db power division should be achieved. No effort was made in this direction, but a semitransparent mirror of this kind should be weighed carefully against a glass one.

IV. HIGH-PASS FILTER

A TE_{01}° high-pass filter is obtained by reducing the diameter of a circular waveguide. The minimum radius essentially fixes the cutoff frequency and the slope of the tapers determines the steepness of the transfer characteristics.

The high-pass filter, Fig. 9, is made of electroformed round copper pipes. Two relatively smooth tapers connect the cutoff section to $\frac{7}{16}$ inch-diameter waveguide. The cutoff section has a constant diameter of 0.260 inch and is 1 inch long. The over-all length of the filter is 3.8 inches.

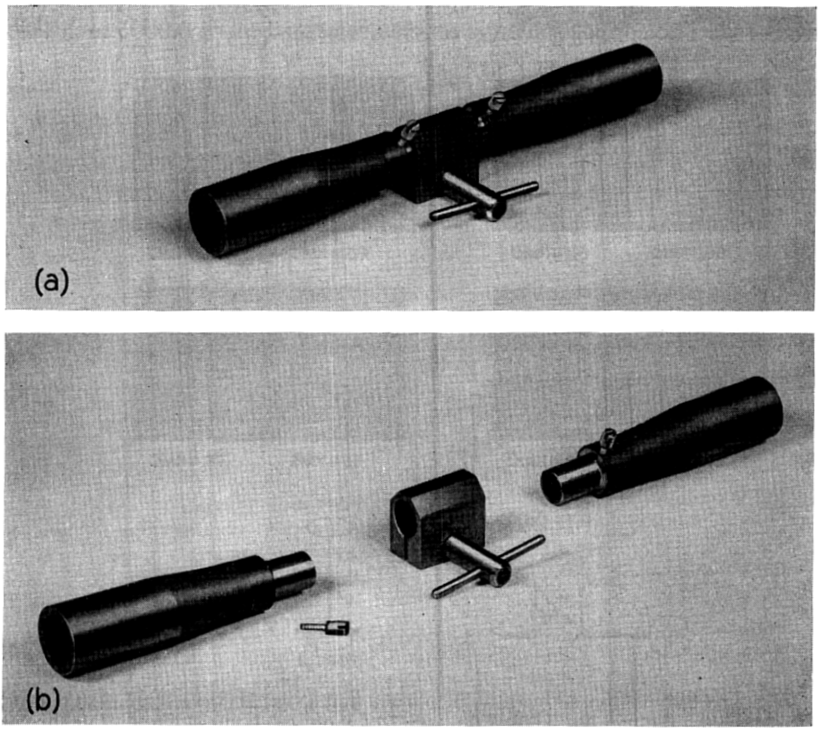

Fig. 9 — (a) TE_{01}° high-pass filter; (b) exploded view.

The end size of the high-pass filter was selected because we already had on hand tapers from $\frac{7}{16}$ to 2 inches in diameter.[6] In a final design of a band-splitting filter it is not necessary to pass through the intermediate size of $\frac{7}{16}$ inch, and consequently the filter can be more compact than the one shown in Fig. 2.

In order to appreciate the high-pass filter behavior at frequencies close to cutoff, transmission and reflection were measured point by point, as shown in Fig. 10. In an ideal high-pass filter, power at frequencies above cutoff should be transmitted completely, but this implies that the taper should match a waveguide of a certain admittance to another

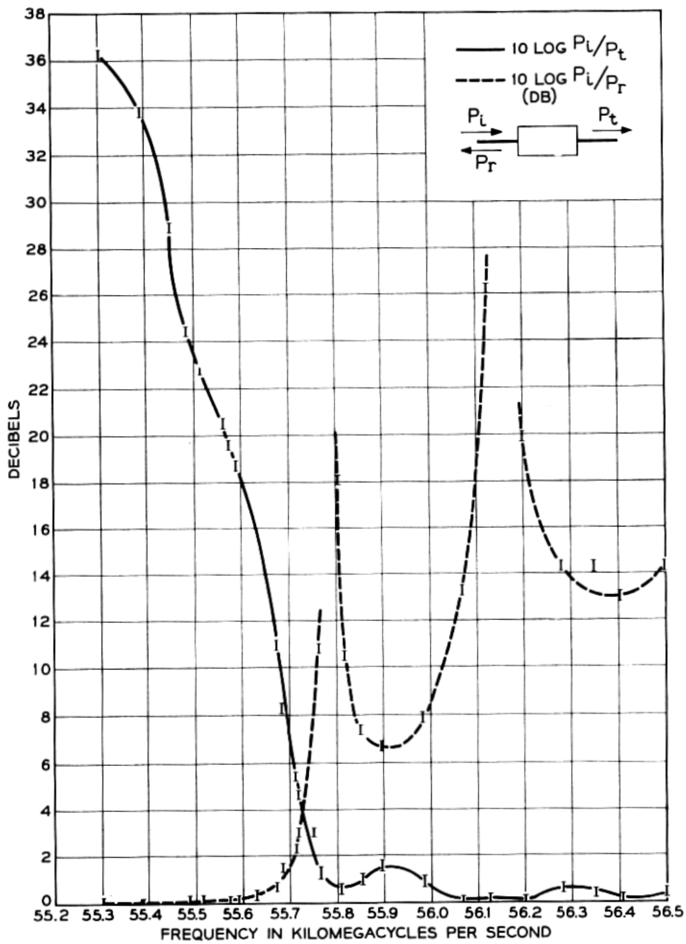

Fig. 10 — Transmission and reflection of high-pass filter (without tuning screws).

of admittance close to zero, which requires extremely long tapers. Our tapers are short, and Fig. 10 shows that the maximum unwanted reflection above cutoff is 6.6 db. This reflection can be reduced by using polyethylene tuning screws. The transmission and reflection of the taper with tuning screws, as seen in Fig. 11, show that the maximum unwanted reflection has been reduced to 16.8 db without changing substantially the transmission characteristic. The difference between the frequencies at which transmission and reflection losses are below 1 db is 160 mc. This is a very sharp cutoff.

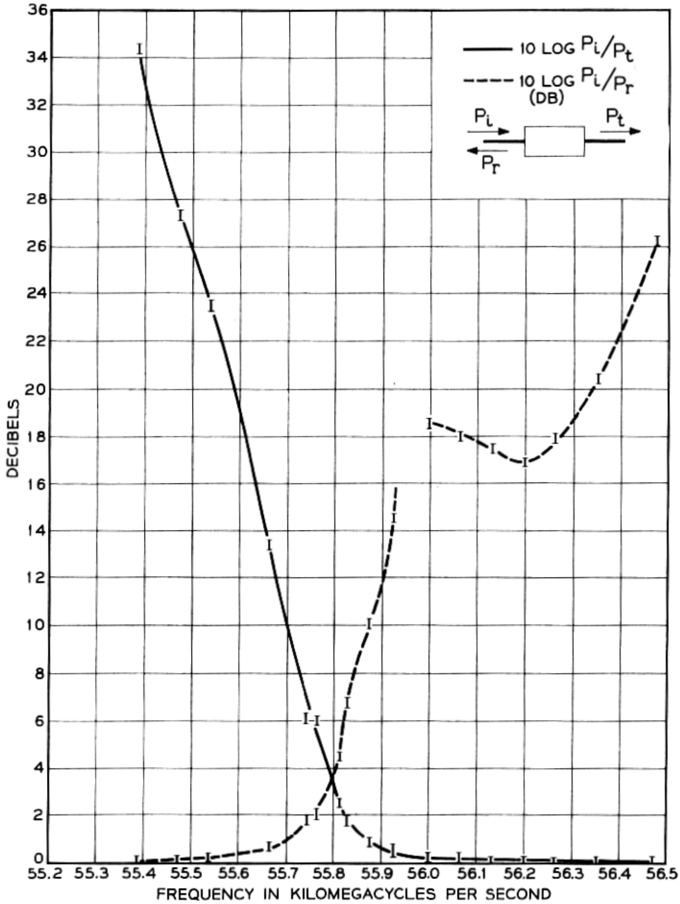

Fig. 11 — Transmission and reflection of high-pass filter (with tuning screws).

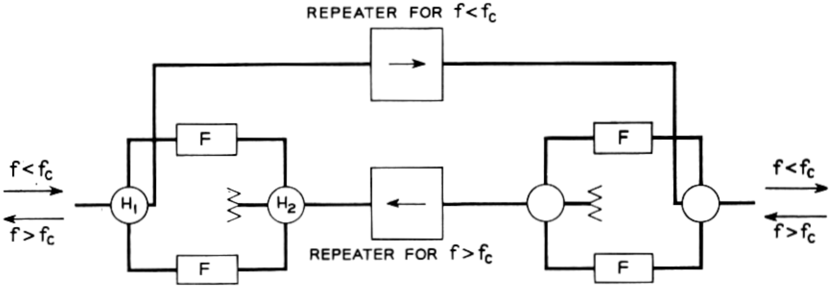

Fig. 12 — Two-way transmission on a single waveguide using two band-splitting filters.

V. ELBOW

The elbow, as mentioned earlier, is derived from the hybrid by replacing the semitransparent mirror with a metal plate. The insertion loss is 0.2 ± 0.05 db.

VI. ANOTHER POSSIBLE USE FOR A BAND-SPLITTING FILTER

This filter allows using a single waveguide to transmit in both directions. Fig. 12 shows one of the possible arrangements. Two identical band splitting filters are used. Calling f_c the cutoff frequencies of the filters F, the reader can check that frequencies $f < f_c$ can travel towards the right and frequencies $f > f_c$ can travel towards the left.

Power leaving the repeater for $f < f_c$ can leak into the repeater for $f > f_c$ only by passing through cutoff filters, and consequently that leakage can be made arbitrarily small. On the other hand, power leaving the repeater for $f > f_c$ can leak into the repeater for $f < f_c$ because of unbalance in the hybrids H_1 and H_2. This leakage can be reduced if necessary by including between hybrid H_1 and the repeater a filter like the one shown in Fig. 13. It consists of a hybrid and two high-pass filters like those described previously.

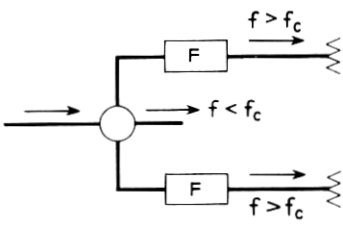

Fig. 13 — Filter to eliminate high frequencies.

VII. CONCLUSIONS

A constant-resistance filter capable of dividing a wide band in two has been described. It can easily handle one octave in the millimeter region with only 1.5 db insertion loss for each subband. The splitting transition takes place in a very narrow band (160 mc). Another use of the filter: it allows using a single waveguide to transmit in both directions.

Two of the components of the filter are important devices: an elbow and a hybrid. Both are quasi-optical and operate easily over one octave in the millimeter region. The elbows allow sudden 90° turns of a 2 inch-diameter multimode waveguide with relatively low insertion loss 0.2 ± 0.05 db. Without them the band-splitting filter would be very bulky. The importance and uses of the hybrid need hardly any comment.

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