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Band-Stop Filters for High-Power Applications

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***Abstract*—There are several advantages to the use of band-stop filters, rather than band-pass filters, in many systems. This is shown to be particularly true when signals at high-power levels must be transmitted or rejected.**

A formula has been derived which expresses the external Q of each resonator in a band-stop filter in terms of the element values of the normalized low-pass prototype and the parameters of the frequency transformation. The peak power capacity of iris-coupled waveguide cavity filters and TEM filters using capacitively coupled inductive stubs is then determined in terms of the external Q of the first resonator and the dimensions of the resonator. Experimental results given for a waveguide band-stop filter show good agreement with theory.

I. Introduction

IN THE recent literature a number of articles have appeared expounding the virtues of band-stop filters in lieu of band-pass filters for many applications [1], [2]. In cases where a high rejection loss is required over a relatively narrow frequency band, and where low insertion loss is needed at a frequency close to this rejection band, the band-stop filter is the more efficient device. The band-stop filter can also be more easily aligned to exhibit its prescribed response. Each resonator can be independently adjusted so that the coupling from the main transmission line to that resonator yields the specified external Q. This is accomplished by detuning all other resonators. When all of the couplings are properly set, the band-stop filter is then aligned by adjusting the individual cavity resonators in turn until peak rejection is obtained. In practice, very little additional trimming is required beyond this point. In Section II of this paper, a simple expression is derived which enables the design engineer to determine the external Q of each resonator directly in terms of the required performance and the element values of a normalized low-pass prototype filter [3].

The band-stop filter offers advantages when considered as part of a diplexer or multiplexer. A combination of band-pass and band-stop filters can be designed to approximate a true complementary pair, presenting a matched input over a very wide band of frequencies [4]. Band-stop filters can also be used in cascade connection with other filters to provide more complex rejection characteristics [5]. This is a particular advan-

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tage in high-power systems since the high power generally is present only in narrow frequency bands. These frequency ranges are normally known in advance. Therefore, a band-stop filter offering high rejection to this band and capable of withstanding the expected levels of power can be used ahead of band-pass or other filters designed to reject signals at more moderate power levels.

For high-power systems, the band-stop filter offers still other advantages. It will be shown that, when designed to reject high-power signals, only the input resonator of the band-stop filter need be capable of withstanding the full applied power. When a high-power signal is transmitted through a band-stop filter, the peak power capacity of the filter is essentially that of the input waveguide. Not only is the power-handling capacity of such a filter only slightly reduced as a result of the small perturbations which exist in the main waveguide, but also such filters generally have lower dissipative losses than comparable band-pass filters, so that the heating problem is minimized. It was demonstrated experimentally that the power-handling capacity of band-stop filters is in close agreement with the breakdown potential derived from theory. It has been observed by other investigators that the average power breakdown is significantly lower than the peak power breakdown in the same filter structure. Experimental data have indicated that this decrease in power-handling capacity, when high average powers are applied, results primarily from the heating of the resonators. With proper care and design, and adequate cooling, this average power capability can be increased.

II. External Q of Individual Resonators

The design of band-stop filters exhibiting prescribed insertion-loss characteristics has been described by Matthaei, Young, and Jones [2] in terms of the elements of a low-pass prototype filter. For a filter having a narrow bandwidth, the external Q's of the individual resonators can be expressed directly in terms of the elements of the low-pass prototype filter and the parameters of the frequency transformation. In the circuit of Fig. 1(b), the low-pass prototype circuit is realized by series resonant circuits shunting a transmission line at intervals equal to an odd multiple of a quarter wavelength. Figure 2 defines the frequency transformation and its important parameters. Reference [2] defines a reactance slope function

$$x_i = \frac{\omega_0}{2} \cdot \frac{dX_i}{d\omega}\bigg|_{\omega=\omega_0} \tag{1}$$

where X_i is the susceptance of the ith resonator. For the constant-impedance line structure of Fig. 1, it has also been shown that

$$\frac{x_i}{Z_0} = \frac{1}{\omega_1' w g_i} . \tag{2}$$

At the 3-dB bandwidth points of an individual resonator, the reactance in parallel with the line is equal to $-Z_0/2$ or $+Z_0/2$, while at ω_0 the reactance is zero. Thus the change in X_i is equal to $Z_0/2$ when $d\omega$ corresponds to half of the 3-dB bandwidth. Then, from (1)

$$x_i = Q_{ex_i} \frac{Z_0}{2} \tag{3}$$

where $Q_{ex_i} = \omega_0/2d\omega$ is the external Q of the ith resonator. Then, substituting (3) into (2), one obtains

$$Q_{ex_i} = \frac{2}{\omega_1' w g_i} . \tag{4}$$

An analysis of the case of parallel resonant circuits connected in series with the line at odd quarter-wavelength intervals yields the same result.

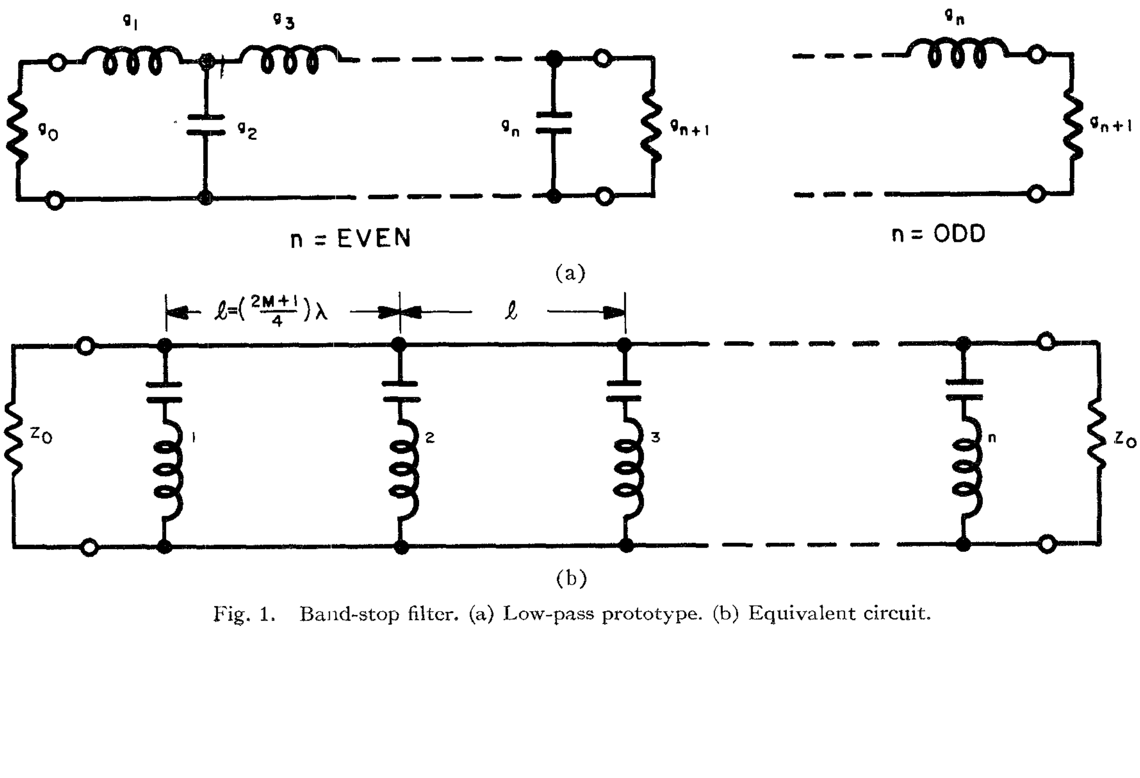

Fig. 1. Band-stop filter. (a) Low-pass prototype. (b) Equivalent circuit.

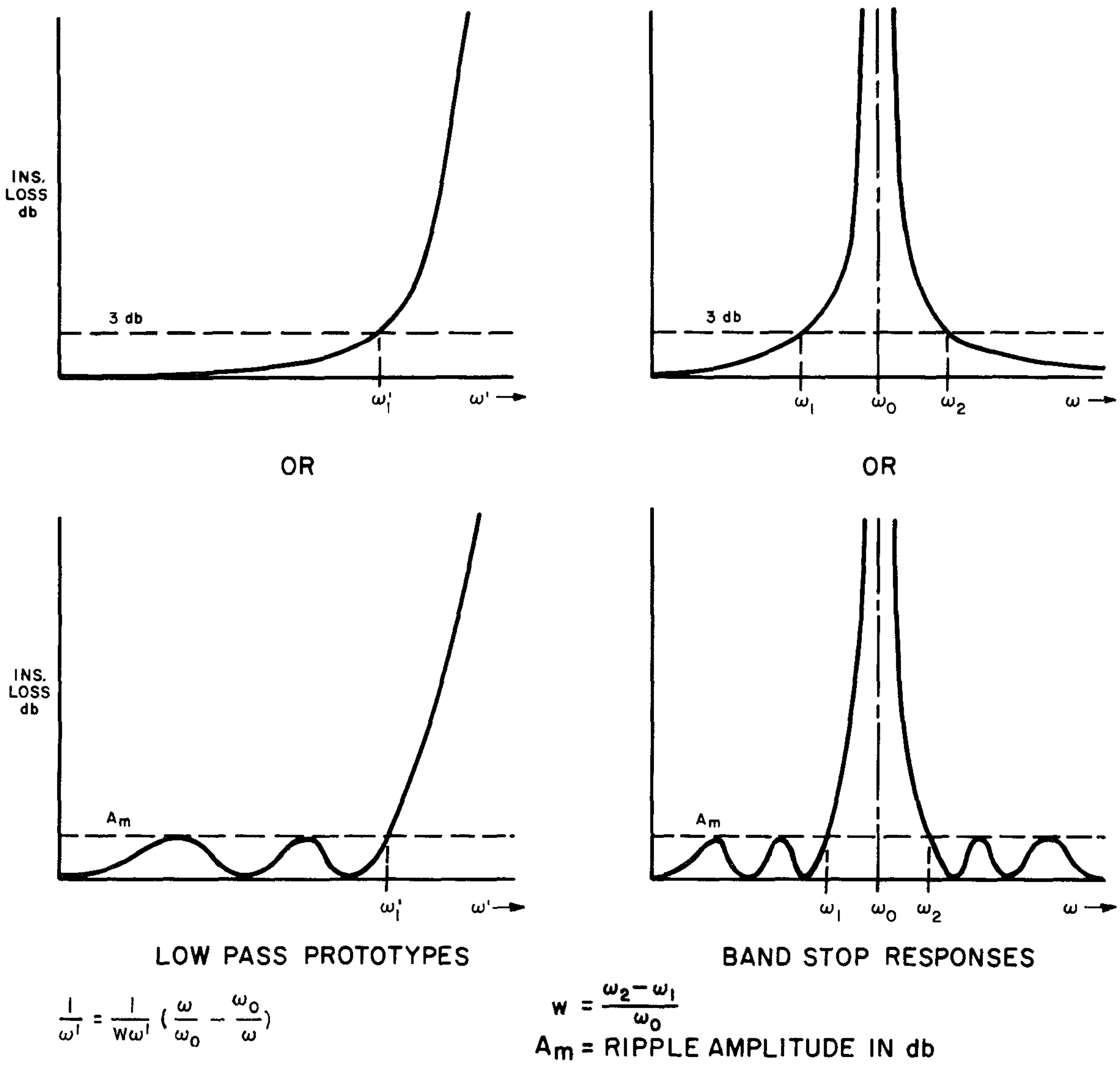

Fig. 2. Ideal filter characteristics.

It is extremely useful for design purposes to be able to express the external Q of each individual resonator in a band-stop filter in terms of the parameters of the low-pass prototype and the prescribed performance characteristics. A simple experimental procedure for adjusting the coupling of the individual resonators to achieve the required Q_{ex} value was suggested earlier. Furthermore, the peak-power-handling capacity of the filter can readily be determined from the external Q of the first resonator.

III. High-Power Characteristics: Rejection Mode of Operation

Only the first resonator of a band-stop filter, designed to offer peak rejection to a high-power signal, is exposed to the maximum power level of the incident signal. The power incident upon all subsequent resonators is substantially reduced. This can easily be seen by examination of the circuit of Fig. 1(b). In the vicinity of its resonant frequency, each resonator exhibits a short circuit across the transmission line. Since the length of line between resonators is an odd quarter wavelength, the first resonator appears as a short circuit shunted by a high impedance. Both the voltage across the first resonator and the current flowing into the line beyond this resonator are extremely small. Therefore, very little of the incident signal impinges upon any of the subsequent resonators. A similar analysis of parallel resonant circuits connected in series with the line at quarter-wavelength intervals leads to the same conclusion.

Since the first resonator of the band-stop filter is exposed to the full power incident upon the filter, this resonator must be designed to be capable of operation at high-power levels. In Section II, the external Q of the resonator was derived. This parameter can be obtained with a variety of structures. The peak field within the resonator is dependent upon both the external Q and the structural realization of the resonator. Two of the more commonly used types of resonators will now be considered.

Waveguide Cavity Resonator

Consider a single resonant cavity coupled through an iris to the side wall of a waveguide excited by a generator of voltage E_g. The generator and termination impedances are equal to Z_0 [see Fig. 3(a)]. (It is assumed that the characteristic impedance of the cavity resonator is also Z_0.) Looking back from the cavity toward the coupling iris, a Thevenin equivalent generator can be defined as shown in Fig. 3(b). The coupling reactance can also be idealized by a transformer having a turns ratio of $1{:}K$ [see Fig. 3(c)]. The equivalent network of Fig. 3(d) is then obtained when the source voltage and impedance are referred to the secondary terminals.

In the case of a narrow-band resonator, the reactance of the cavity is given, near resonance, by

$$X = jZ_0 \left| \tan\left(\theta_0 + \Delta\theta\right) \right| \tag{5}$$

where θ_0 is the electrical length of the resonator at center frequency. If θ_0 is a half wavelength and $\Delta\theta$ is small, this can be written approximately as

$$X = jZ_0 \Delta\theta. \tag{6}$$

At the half-power points, the magnitude of X is equal to the equivalent source impedance

$$\left| X_{3\text{db}} \right| = \frac{Z_0 K^2}{2}. \tag{7}$$

Furthermore, in the narrow-band approximation

$$\frac{\Delta\theta_{3\text{db}}}{\theta_0} \approx \frac{\Delta\omega_{3\text{db}}}{\omega_0} = \frac{1}{2Q_{ex}}. \tag{8}$$

Therefore,

$$\left| X_{3\text{db}} \right| = \frac{Z_0 K^2}{2} = \frac{Z_0 \theta_0}{2Q_{ex}}. \tag{9}$$

Thus the turns ratio K is found to be

$$K = \sqrt{\frac{\pi}{2Q_{ex}}}. \tag{10}$$

The resonator input current is

$$I_n = \frac{(KE_g/2)}{(K^2 Z_0/2)} = \frac{E_g}{KZ_0}. \tag{11}$$

The maximum voltage in the resonator occurs at the mid-point of the cavity, or a quarter wavelength back from the short-circuit termination. At this point, the voltage is

$$E_{\max} = Z_0 I_n = \frac{E_g}{K} = E_g \sqrt{\frac{2Q_{ex}}{\pi}}. \tag{12}$$

While a single resonator has been considered, it can readily be shown that this is also the expression for peak voltage in the input resonator of a multiresonator filter. The incident power in the main waveguide is given by the expression

$$P_{\text{in}} = \frac{E_g{}^2}{8Z_0} \tag{13}$$

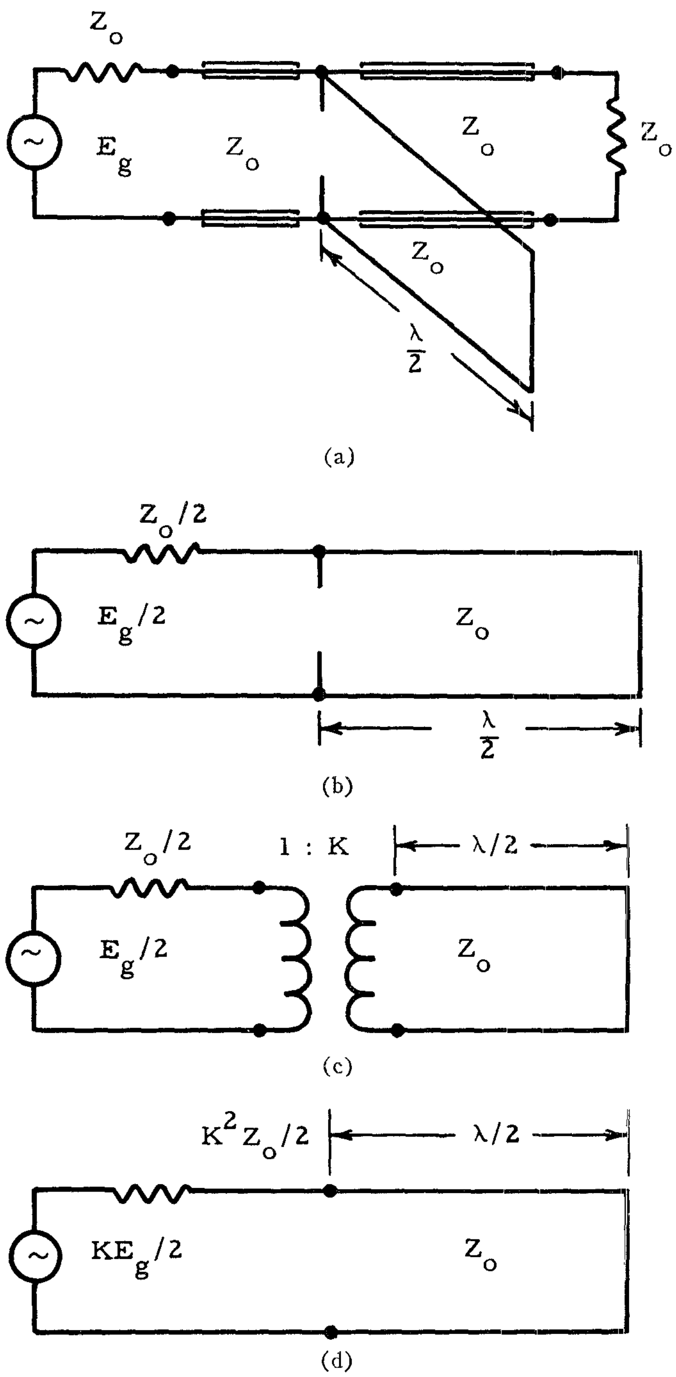

Fig. 3. Single-band reject resonator. (a) Single resonator coupled to main line. (b) Thevenin equivalent generator exciting cavity. (c) Equivalent circuit of Fig. 1(b). (d) Circuit of Fig. 1(c) referred to secondary.

where E_g is the peak (rather than the rms) generator voltage. Furthermore, Z_0 is given approximately as

$$Z_0 = 377 \frac{b}{a} \left(\frac{\lambda_g}{\lambda} \right) \tag{14}$$

where b is the waveguide height, and a is the waveguide width. Upon substitution of (12) and (14) into (13), the following formula is obtained:

$$P_{\text{in}} = \frac{E^2_{\max}}{3016} \left(\frac{a}{b} \right) \left(\frac{\lambda}{\lambda_g} \right) \left(\frac{\pi}{2Q_{ex}} \right). \tag{15}$$

The peak power at breakdown is thus determined when E_{max} is equal to the breakdown potential of air (75,000 $\times b$ volts at normal temperature and pressure; b is expressed in inches).

For the specified side-wall coupling, the electric field is extremely low at the coupling aperture. Therefore, the power-handling capacity will not be adversely affected by the size of the aperture. However, high currents will be flowing in that region. Therefore, good practice dictates that the usual design precautions be observed [6], [7]; sharp edges should be avoided, and all metal joints should be smooth and unbroken. All surfaces in high-current areas should be silver-plated to reduce the power dissipation and thereby minimize local heating. Since the breakdown potential is in approximately inverse proportion to the absolute temperature [8], local "hot spots" can sharply reduce the power-handling capacity of the filter. When high levels of CW power are specified, it is advisable to provide the filter with external cooling. Pressurization of the waveguide will further increase the breakdown potential. To a first approximation, the breakdown potential is proportional to the absolute pressure of the waveguide [9].

Band-stop filters employing parallel resonant cavities, iris-coupled to the top wall of a waveguide at quarter-wavelength intervals, have also been analyzed. The peak voltage in the resonator in this case is identical to that of the side-wall coupled resonator (12). However, the top-wall coupled resonator is effectively in series with the main waveguide, so that a relatively high electric field exists across the coupling aperture. Therefore, the design of the aperture must take these high fields into account [7].

Capacitively Coupled Stubs in TEM Lines

The equivalent circuit of Fig. 1(b) can be realized, in TEM lines, by indictive stubs capacitively coupled to the line at quarter-wavelength intervals. As in the case of capacitively end-loaded coaxial resonators, the maximum voltage in the resonator appears across the capacitor. Since the capacitive gap spacing is generally small, breakdown is most likely to occur across the gap of the first resonator.

For a simple series resonant circuit, the reactance of the resonator in the vicinity of resonance is given approximately by

$$X \approx X_0 \frac{2\Delta\omega}{\omega_0} \tag{16}$$

where X_0 is the magnitude of reactance of the capacitor or inductor at resonance [10]. At the 3-dB points, the reactance is equal to the total resistance shunting the resonator. Thus, for a single resonator in parallel with a matched generator and load [see Fig. 1(b)]

$$| X_{3db} | = \frac{2\Delta\omega_{3db}}{\omega_0} \cdot X_0 = \frac{Z_0}{2} \cdot \tag{17}$$

Since $2\Delta\omega_{3db}/\omega_0$ is equal to Q_{ex}, the capacitive reactance at resonance is

$$| X_{0c} | = \frac{Z_0}{2Q_{ex}} \cdot \tag{18}$$

Thus the peak voltage across the capacitor at resonance is

$$E_c = \frac{E_g}{Z_0} X_{0c} = \frac{E_g Q_{ex}}{2} \tag{19}$$

where E_g is the peak generator voltage. The power incident upon the line is

$$P_{inc} = \frac{E_g^2}{8Z_0} = \frac{E_c^2}{2Z_0 Q_{ex}^2} \cdot \tag{20}$$

The breakdown power level is then determined by the potential at which the capacitor arcs over. If the capacitive gap is filled with dielectric to increase the power-handling capacity of the filter, the field in the inductive portion of the resonator must be examined to determine that breakdown will not occur there. Since (19) also describes the voltage across the input to the inductive network, which is generally realized as a short-circuited stub line, the breakdown conditions in the stub can easily be analyzed.

IV. High-Power Characteristics: Transmission Mode of Operation

A band-stop filter is capable of handling almost the full power for which the input line is rated, when it is operating in its pass band. The resonators are loosely coupled to the main line so that very little power is coupled from the line to the resonator. Since these resonators are now operated away from resonance, the peak field buildup considered earlier does not occur. The disturbance to the main line introduced by the resonator coupling iris must be examined in the same way as any discontinuity located in a high-power system. Thus, the possibility of high fields across a gap, or high current across a sharp edge or junction, should be investigated. The effects of discontinuities placed in the waveguide to match the resonators should be scrutinized. When operating near the stop band, the presence of standing waves between the resonators should also be analyzed. However, it is unlikely that any of the aforementioned regions would seriously detract from the power-handling capacity of the filter.

In general, band-stop filters are used to transmit high power when there is a requirement for low-loss transmission close to a sharply defined rejection region, largely because band-stop filters exhibit lower pass-band dissipation than band-pass filters with similar rejection slopes. The problem of heating due to power loss is therefore not so severe as would be encountered in the case of band-pass filters for similar operation. However, one must examine the total filtering system to establish whether or not heating will be a problem. For example, a band-stop filter, operating in its transmission mode at a power level well below the rating of the input guide, may be far from breakdown. If the same filter is required simultaneously to reject a high-power signal at a different frequency, heating due to the transmitted signal may reduce the breakdown potential for the rejection frequency. Thus, where two different high-power signals are introduced into the band-stop filter, and one of the frequencies is to be rejected, the same considerations described earlier with regard to temperature apply. While cooling might not be required in the presence of either signal, it may be dictated when both signals are present. This situation would become more pronounced as the frequency separation between the transmitted signal frequency and the rejection band is reduced, since losses in the transmission mode increase rapidly as the signal frequency approaches the cutoff of the filter.

V. Experimental Results

A band-stop filter was designed to transmit a 10-kW CW signal in the band from 6300 to 6400 Mc while simultaneously rejecting a 10-kW signal in a narrow band around 6210 Mc. The design required an input resonator exhibiting an external Q of 115. The cross-sectional dimensions of the cavity were $a = 1.872$ inches and $b = 0.872$ inch. From (15) the maximum rejection power was determined to be 36.1 kW at room temperature and one atmosphere of pressure. The filter was actually tested with an internal pressure of 2 psig, which would increase the theoretical breakdown power to 46.5 kW.

The filter was tested for breakdown under both pulse and CW conditions. In the transmission mode of operation, the filter exhibited no breakdown when a pulse power of 50 kW was applied. The filter also operated without breakdown with a CW signal of 10 kW at 6300 Mc. Testing was not carried beyond this point since the capability of the filter to handle the specified power was adequately demonstrated.

In the rejection mode, the filter exhibited a pulse power breakdown at approximately 50 kW when a 6210-Mc signal with a duty cycle of 0.001 was applied. Under CW conditions at the same frequency, breakdown occurred at a power level of 11 kW. This breakdown occurred after RF power was applied for a period of approximately 3 minutes, which corresponded closely to the time required for the filter temperature to stabilize. At breakdown, with water cooling, a temperature rise of 100°C was measured on the outside wall of the resonator farthest from the cooling tubes.

The peak power breakdown corresponded closely to the capability predicted by (12). This theoretical limit reduces to approximately 25 kW when a temperature rise of 100°C is considered. Internal and localized heating within the resonator was probably significantly greater than the temperature rise recorded on the outside walls would indicate. Therefore, it is not surprising that breakdown occurred under average power conditions at a somewhat lower level.

VI. Conclusions

The advantages realized by the use of band-stop filters in high-power systems have been described. Formulas have been derived which are capable of predicting the breakdown power levels for such filters. One may consider breakdown under peak power conditions solely in terms of the breakdown potential in air at normal temperature and pressure. However, when a filter is exposed to high levels of average power, other problems are associated with the design.

In order that a filter be capable of withstanding high incident peak power levels, a number of design rules have been given which are applicable for both band-pass and band-stop filters. In addition to the peak fields within a resonator, sharp corners, projections, and irregularities within the structure should also be avoided. Such discontinuities can give rise to high, localized, field intensities, sufficient to cause breakdown. In addition to these considerations, it is extremely important that filters subjected to high average powers have no imperfections capable of causing high or localized dissipation—and, therefore, heating. It is necessary to utilize external cooling when the total power dissipation produces a significant temperature rise. In addition, the power level at which breakdown occurs can be significantly reduced if, despite external cooling, "hot spots" occur within the resonator. Therefore, it is important that the plating on cavity surfaces be uniform and free from blisters, tarnishing, etc. Soldered or brazed joints should be continuous and free from external buildups. Particular care should also be exercised if tuning screws are introduced through the walls of the cavity.

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