# The Arc Loss of Multimegawatt Gas Discharge Duplexers

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***Abstract*—The arc loss of a multimegawatt gas discharge switch is analyzed in the approximation that discharge skin depth is small compared to the discharge container dimensions. Experimental agreement with the results of this analysis is found in several respects: 1) arc loss varies linearly with iris height; 2) arc loss varies inversely with the one fourth root of average peak power; 3) calculated ratios of shunt to series arc loss agree with experimental loss measurements on gas filled TR and ATR duplexer windows. These results have been of particular value in predicting both the loss and power handling capability of extremely high power balanced TR and ATR duplexers from tests on simple shunt mounted discharge windows. It is shown that, for the same iris height, series windows are superior in power handling capability to shunt windows, with the result that a balanced ATR duplexer has two to four times the power handling capability of a balanced pre-TR duplexer.**

## Introduction

A GAS DISCHARGE is frequently used for very high power microwave switching applications because of the low losses that can be realized, and because of the discharge's unique property that switching efficiency improves with increasing peak power. The arc loss of such discharges is the subject of this paper.

The discharges studied occur in very high power microwave duplexers, a switching device used in radar systems to connect the transmitter and receiver to a common antenna. In such duplexers, the gas discharge normally occurs immediately behind a resonant window iris which, for the purposes of switching, can be placed either in series or in shunt with an appropriate waveguide line.

When in shunt, the discharge window forms the basic element of a pre-TR duplexer, as shown on Fig. 1. The operation of this duplexer is apparent from the diagram. During the transmit cycle, high power microwave pulses pass down the transmitter arm and through a 3-dB hybrid which splits the power equally between two waveguide channels. The incident power than falls on the dual pre-TR window, creating an intensve discharge, and the power is reflected back through the hybrid and out the antenna port. During the receive cycle, the returning radar echo signal enters the antenna port at some time in the interpulse period, and again passes through the hybrid. By this time the dual discharge window has "recovered" from the transmitter pulse; and the echo signal passes through the window, through a second hybrid and out the receiver port. Low level bandwidth in this device is achieved by using an array of shunt mounted elements in addition to the discharge window.

The basic element of an ATR duplexer is a discharge window in series with the waveguide line, as shown on Fig. 2. In this duplexer the antenna and load terminals are reversed from the pre-TR case; and the discharge windows are located in the broad walls of the waveguide. Bandwidth is again achieved by using an array of such elements. At a distance of one quarter wavelength behind each window is an electrical short which presents an open circuit at the window, when the window is in the unfired state. During transmit cycle, the incident power is split by the first hybrid, fires the discharge windows, and passes through the second hybrid to the antenna port. On receive, the returning echo signal enters the antenna port and passes through the second hybrid. The signal is then reflected by the open circuit presented by the unfired windows and passes back through this hybrid into the receiver channel.

A better idea of the actual construction of a duplexer window mount can be obtained from Fig. 3, which shows the window mount for a balanced ATR duplexer in S band. It is noticed that this structure is quite compact, which results from the fact that the discharge arc loss is small, usually less than 0.1 dB. As shown, the mount consists of an array of gas filled quartz tubes mounted in the broad wall of a section of dual channel waveguide. The discharge windows are formed by iris slits, cut in the waveguide wall, which expose these tubes to microwave energy [1]. A particular advantage of this structure is that the tubes are field replaceable.

Both the duplexers described have about the same insertion loss between antenna and receiver ports. This can be made as low as 0.5 dB, for a ten percent bandwidth, including the loss of a crystal protector in the receiver channel. In the balanced ATR duplexer the isolation between transmit and receive channels is furnished by the hybrid, and is typically about 27 dB over a ten percent bandwidth. This figure is 40 to 50 dB for the pre-TR duplexer where additional isolation is provided by the discharge windows. However, as will be shown in this paper, the ATR duplexer has a much higher inherent power handling capability.

In the analysis that follows, the discharge is treated as a lossy conductor of fixed surface area and varying thickness, given by the skin depth which varies with

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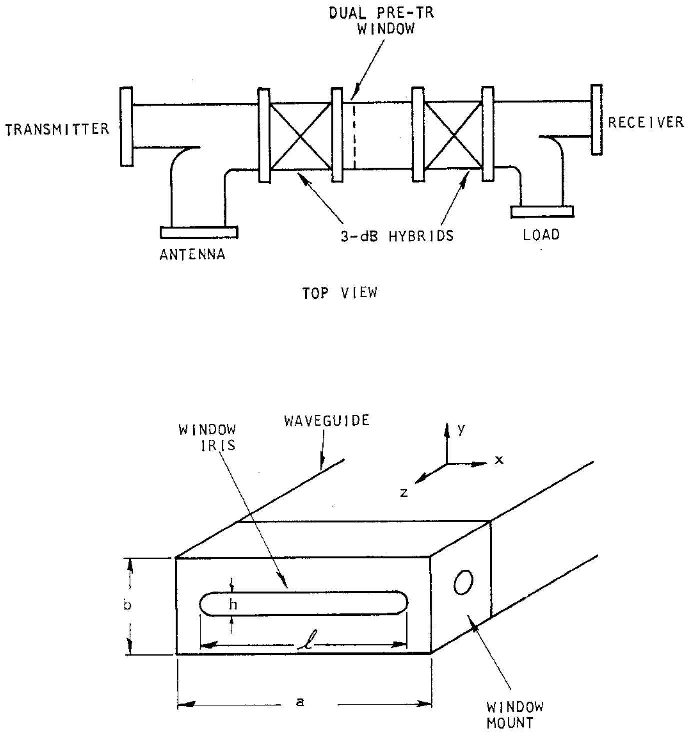


Fig. 1. Balanced pre-TR duplexer and shunt waveguide window.

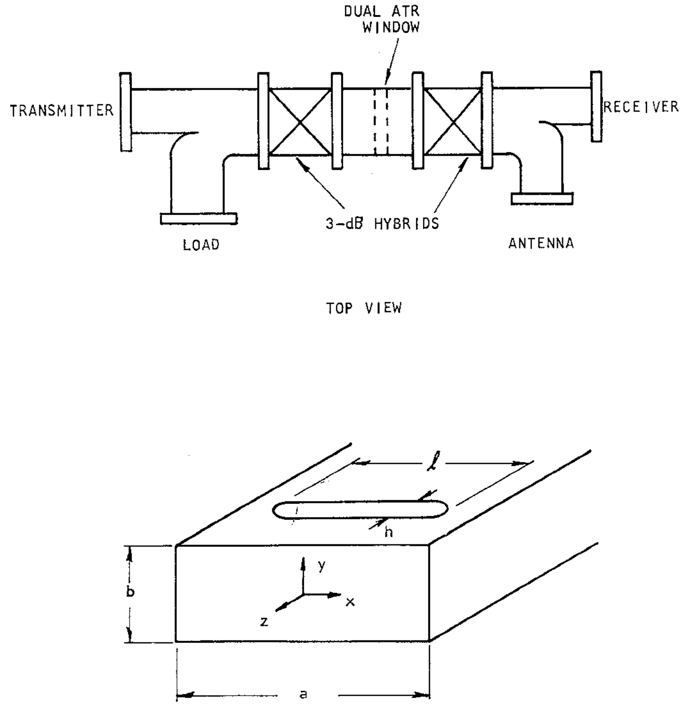


Fig. 2. Balanced ATR duplexer and series waveguide window.

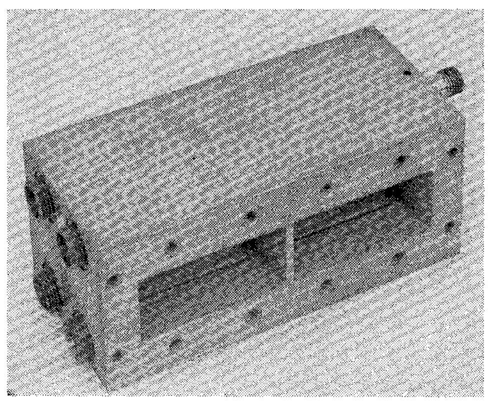

Fig. 3. Photograph of balanced ATR duplexer window mount.

peak incident power. It is assumed that the skin depth is smaller than the discharge container dimensions. This situation is always realized with full cylinder windows in very high power switching applications. The analysis neglects the detailed physics of the discharge considered by other investigators [2]; and the results to be described are independent of the nature of the gas used.

## Analysis of Discharge Arc Loss

A discharge window, mounted in shunt with a waveguide line, is shown schematically on Fig. 1. In this figure $l$ and $h$ are respectively the iris length and height; ($a$) is the waveguide width, and ($b$) is the waveguide height. When high power microwave energy is incident on this window a very bright gas discharge is formed immediately behind the iris and adjacent to the inside wall of the quartz bulb. Visibly, the discharge extends only a few hundredths of an inch into the bulb interior and is so intense that virtually all power not dissipated in the discharge is reflected. Consequently, it is very nearly a perfect short circuit. Because of this, it is assumed that distortion of the electromagnetic field distribution of the principal waveguide mode, by the iris, can be neglected even though the window iris is approximately a half wavelength in size. Losses in the quartz bulb are also neglected since in practice, where these are significant, they can always be determined independently and subtracted from the measured total loss of the discharge and its container.

The arc loss is defined as the ratio of power absorbed in the discharge to the power incident. Under the conditions described, the discharge can be treated as a thin strip of lossy conductor with surface area equal to that of the iris, and with thickness equal to a skin depth. For a shunt mounted window terminating a waveguide, as shown on Fig. 1, this leads to the expression

$$A_T = \frac{4R_s}{Z}\frac{hl}{ab}\left(1 + \frac{a}{\pi l}\sin\frac{\pi l}{a}\right). \tag{1}$$

This result is obtained by integrating the electric and magnetic fields of the $TE_{10}$ waveguide mode over the iris area with the origin of coordinates chosen in the center of the waveguide broad wall as shown in the figure. $Z$ is the characteristic waveguide impedance; and the ratio $4R_s/Z$ is the arc loss of the full waveguide cross section when terminated by the surface resistance, $R_s$. The factor four arises from the fact that the line current is effectively doubled at the short circuit created by the shunt window. Since the discharge occupies only the iris area, the arc loss of the full waveguide cross section is reduced by $hl/ab$—the ratio of the iris area to the area of the waveguide cross section. The additional factor in parenthesis occurs because the current at the window is not uniform over the waveguide width, but varies sinusoidally from a maximum at the waveguide center to zero at the side walls.

All the characteristics of the discharge are contained in $R_s$, the discharge surface resistance.

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\omega\mu_0}{2\sigma}}. \tag{2}$$

In this expression, $\sigma$ is the discharge conductivity; $\delta$ is the skin depth; $\omega$ is the radian microwave frequency; and $\mu_0$ is the permeability of free space. The discharge conductivity is a complex quantity and normally both its real and imaginary parts would have to be considered in evaluating $R_s$. However, if the neutral gas pressure in the quartz bulb is sufficiently high, then the imaginary part of the conductivity can be neglected compared to the real part [3]. This situation exists in TR tubes which are normally filled to gas pressures of several torr. Consequently, the discharge conductivity is given by the expression

$$\sigma \simeq \frac{ne^2}{m\nu_{\text{eff}}} \tag{3}$$

where the assumption is made that $\nu_{\text{eff}}$, the effective collision frequency, does not vary with electron velocity [4]. Here $n$ is the average electron density; and $e$ and $m$ are, respectively, the electron charge and mass.

At any fixed microwave power level, both electron density and collision frequency vary with the nature of the gas used and the gas pressure. Also the effective collision frequency varies with electron temperature. However, this temperature does not vary appreciably over a wide power range. Meuhe and Fessenden have shown for argon [5], that the electron temperature varies by less than an order of magnitude for a change in $E/p$, the ratio of electric field to gas pressure, of $10^4$. The average value of the electron temperature over this range is about 2.3 electron volts in agreement with Allis's prediction that the mean energy of the electrons in a discharge of any gas is about 3/10 of the lowest excitation potential [6]. Consequently, it is assumed that $\nu_{\text{eff}}$ in (3) is essentially independent of microwave power level. For any given gas and fill pressure, variations in discharge conductivity with microwave power level are then due primarily to changes in electron density.

An expression similar to that given in (1) is found for the series $E$-plane window which can be mounted in either the top or bottom waveguide wall as shown on Fig. 3. This is the basic element of the balanced ATR duplexer mount shown in Fig. 2. The result obtained is

$$A_E = \frac{R_s}{Z}\frac{hl}{ab}\left[\left(1 + \frac{a}{\pi l}\sin\frac{\pi l}{a}\right) + \frac{Z^2}{\eta^2(f/f_c)^2}\left(1 - \frac{a}{\pi l}\sin\frac{\pi l}{a}\right)\right]. \tag{4}$$

An additional term prefaced by the factor $Z^2/\eta^2(f/f_c)^2$ appears due to the presence, in this case, of transverse waveguide currents parallel to the long dimension of the window iris. Also, the factor four is missing because the discharge sees only the full waveguide current. $\eta$ is the impedance of free space, and $f/f_c$ is the ratio of propagating frequency to the cutoff frequency for the $TE_{10}$ waveguide mode.

It is seen from (1) and (4), that both shunt and series arc loss should vary linearly with iris height. When (2) and (3) are combined to evaluate the discharge surface resistance, it is clear that both series and shunt arc loss vary inversely with the square root of electron density. If electron density is directly proportional to window current $I$ which varies as the square root of peak incident power, then these equations also predict that arc loss should vary inversely with the fourth root of peak power.

$$A_{T,E} \sim \frac{1}{\sqrt{n}} \sim \frac{1}{\sqrt{I}} \sim \frac{1}{P_i^{1/4}}. \tag{5}$$

## Power Handling Capability

A quantity of particular interest to the duplexer design engineer is $A_T/A_E$, the ratio of shunt to series arc loss at fixed incident power. An expression for this ratio is found by taking the ratio of (1) to (4).

$$\frac{A_T}{A_E} = 4\frac{R_{sT}}{R_{sE}}\left[1 + \frac{Z^2}{\eta^2(f/f_c)^2}\left(\frac{1-y}{1+y}\right)\right]^{-1} = K$$

$$y = \frac{a}{\pi l}\sin\frac{\pi l}{a}. \tag{6}$$

At the same incident power the shunt and series window see a different current and, consequently, will have different discharge surface resistances. For this reason a distinction is made between the shunt surface resistance $R_{s_T}$ and the series surface resistance $R_{s_E}$.

The surface resistance ratio $R_{s_T}/R_{s_E}$ can be evaluated by considering the arc loss ratio of two windows with no iris opening $(A_T/A_E)_W$. In this idealized situation there is no discharge present and the surface resistances are identical. Consequently, the ratio which results equals the ratio of the squares of the window currents.

$$\left(\frac{A_T}{A_E}\right)_W = 4\left[1 + \frac{Z^2}{\eta^2(f/f_c)^2}\right]^{-1} = \left(\frac{I_T}{I_E}\right)^2. \qquad (7)$$

Since the discharge surface resistance varies inversely with square root of window current, then it also follows that

$$\frac{R_{sT}}{R_{sE}} = \frac{1}{\sqrt{2}}\left[1 + \frac{Z^2}{\eta^2(f/f_c)^2}\right]^{1/4} = \frac{1}{\sqrt{2}}\left[\frac{(f/f_c)^2}{(f/f_c)^2 - 1}\right]^{1/4} \qquad (8)$$

where use has been made of the impedance relationship, $Z = \eta/\sqrt{1-(f_c/f)^2}$.

When (6) and (8) are combined, there results an expression for the arc loss ratio which takes account of the current varying surface resistance, and is a function only of $f/f_c$ and $l/a$, the ratio of iris length to waveguide width.

$$\frac{A_T}{A_E} = K = 2\sqrt{2}\left[\frac{(f/f_c)^2}{(f/f_c)^2 - 1}\right]^{1/4} \cdot \left[1 + \frac{1}{(f/f_c)^2 - 1}\left(\frac{1-y}{1+y}\right)\right]^{-1}. \qquad (9)$$

This result does not hold for small iris heights as is apparent from the fact that it does not converge to the value given by (7) in the limit of zero iris height. This is not a serious drawback since iris lengths less than 0.3 times the waveguide width normally fall outside the practical range of interest to the duplexer engineer. $A_T/A_E$ is seen to be always greater than unity, clearly indicating that for any given incident power the shunt window has a higher loss than the series window. Fig. 4 shows a plot of this ratio vs. $l/a$ for WR 284 waveguide at $f = 2945$ Mc/s. Over the range $0.25 \leq l/a \leq 1$, $A_T/A_E$ is seen to vary from 3.2 to 1.64.

The significance of the arc loss ratio becomes apparent when one considers the relative power handling capability of series and shunt windows. If arc loss varies inversely as the fourth root of peak power then

$$A_T = \frac{KC}{P_{i_T}{}^{1/4}}; \qquad A_E = \frac{C}{P_{i_E}{}^{1/4}} \qquad (10)$$

$$\frac{P_{a_T}}{P_{a_E}} = \frac{A_T P_{i_T}}{A_E P_{i_E}} = K\left(\frac{P_{i_T}}{P_{i_E}}\right)^{3/4}. \qquad (11)$$

In these expressions $C$ is a constant of proportionality involving the window and waveguide dimensions, as well as $f$ and $f_c$. $P_{i_T}$ and $P_{i_E}$ are respectively the shunt and series incident powers, while $P_{a_T}$ and $P_{a_E}$ are the corresponding absorbed powers. When both windows see the same incident power, (11) predicts that the shunt absorbed power is larger than the series absorbed power by the arc loss ratio factor, $K$.

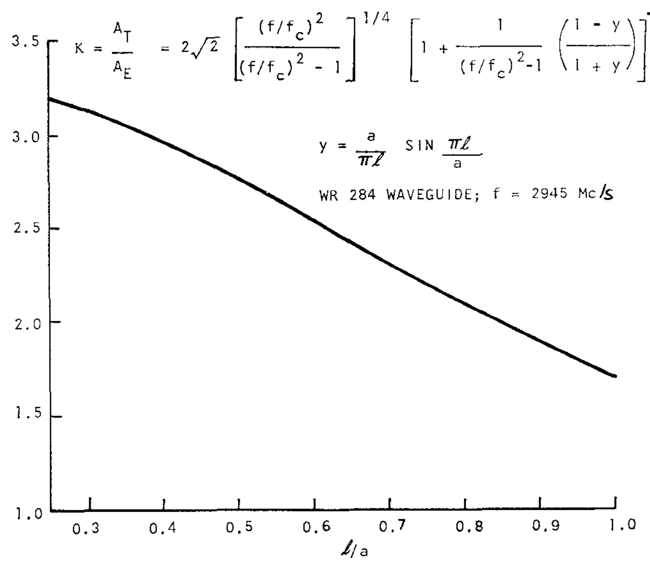


Fig. 4. Arc loss ratio $K$ vs. $l/a$.

$$\frac{P_{a_T}}{P_{a_E}} = \frac{A_T}{A_E} = K. \qquad (12)$$

Conversely, when the absorbed powers are equal, this same equation predicts that the power incident on the series window will be $K^{4/3}$ times the power incident on the shunt window.

$$\frac{P_{i_E}}{P_{i_T}} = K^{4/3}. \qquad (13)$$

## Experimental Results

The linear variation of arc loss with iris height, predicted by (1) and (4), has been verified experimentally for a variety of windows, including those with multiple iris slots. The results are shown on Fig. 5 for a series of windows in $S$ band.

As predicted by (5), arc loss should vary inversely as the fourth root of incident peak power. Figure 6 shows a test of this relationship over two orders of magnitude in peak power—from 200 kW to 20 MW. The effect of varying iris height has been normalized out of the results as seen by the vertical scale which represents arc loss per unit iris height in percent per inch. The theoretical variation of arc loss with peak power, represented by the solid line, has been normalized to the data at one point designated by the arrow. This line has a slope of minus one quarter except at the high power end, where there is a slight upward curvature due to the predominance of electron-ion collisions in the discharge over collisions of electrons with the neutral gas molecules. Conditions of the experimental test are shown in Fig. 6 and it is seen that very satisfactory agreement between theory and experiment exists.

Figure 7 shows the data for an experimental test of the relationships given by (9)–(13). The power absorbed is plotted vs. average incident power for a window mounted first in shunt, then in series with the wave-

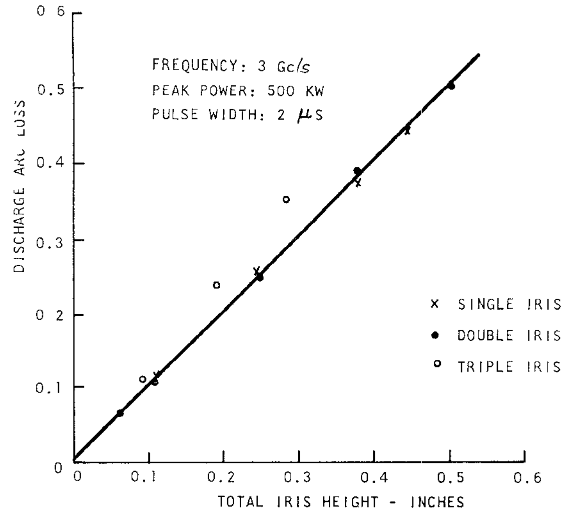


Fig. 5. Discharge arc loss vs. total iris height.

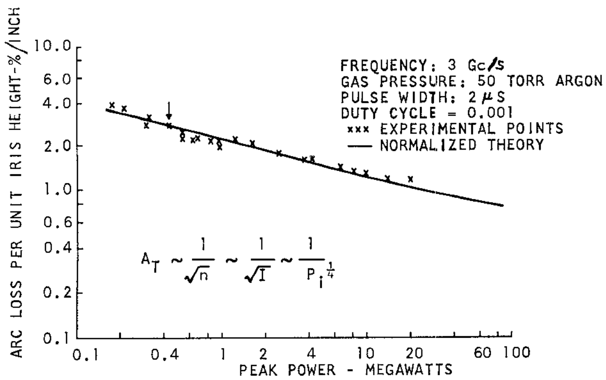


Fig. 6. Discharge arc loss vs. incident peak power.

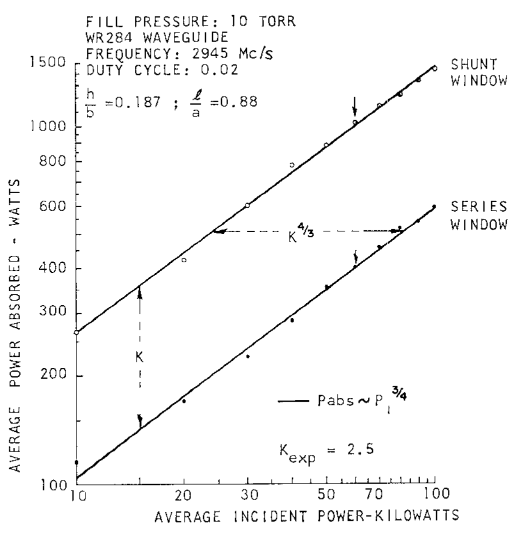


Fig. 7. Power absorbed in window vs. average incident power.

guide. This experiment was conducted at a frequency of 2945 Mc/s under the conditions shown. It is noticed that the power absorbed in both windows varies as the three-fourths power of the incident power as predicted by (11). The theory has been normalized to the experimental data at 60 kilowatts as shown by the arrows. For $l/a=0.88$, (9) gives $K=1.9$. Experimentally $K=2.5$ is found and $K^{4/3}=3.4$ showing that, for the same absorbed power, a series window will switch 3.4 times as much power as a shunt window. The reasons for this discrepancy between theory and experiment are not yet clear, but it is gratifying that the theory yields a conservative estimate which can be reliably used to predict series switching behavior from shunt test results.

## Conclusions

It has been shown that the discharge in extremely high power gas duplexers can be considered as a lossy conductor of fixed surface area, equal to that of the window iris, with varying thickness, given by the skin depth. As a consequence of this, the arc loss varies linearly with iris height and inversely with the fourth root of peak incident power. In addition, a meaningful ratio of shunt to series arc loss can be formed which allows the duplexer engineer to reliably predict the difference in power handling capability of series and shunt windows. Results show that the series window is definitely superior to the shunt window in power handling capability by a factor $K^{4/3}$ where $K$ is the ratio of shunt to series arc loss at fixed incident power. This same ratio applies to the difference in power handling capability between a balanced ATR duplexer, fabricated from series windows, and a balanced pre-TR duplexer, fabricated from shunt windows. Depending on operating frequency and $l/a$, the ratio of iris length to waveguide width, a balanced ATR duplexer has two to four times the power handling capability of a balanced pre-TR duplexer.

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