NEW DIRECTIONAL COUPLERS FOR MULTIMODE CIRCULAR WAVEGUIDES APPLIED TO INTENSE PULSED MICROWAVE SYSTEMS

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Abstract

Three new types of directional couplers are described for use in overmoded circular waveguide operating in the TM_{01} mode. The types are (1) circular/rectangular waveguide multihole couplers, (2) circular waveguide/coaxial multihole couplers, and (3) circular waveguide loop couplers. These directional couplers are designed to diagnose intense pulsed microwave systems in the frequency range 3 - 18 GHz. Coupling coefficients vary between 50 dB and 70 dB with directivities between 13 dB and 20 dB. These devices have been used to measure the output powers of relativistic magnetrons and backward wave oscillators (BWOs) in the power range 100 MW to 300 MW.

Circular Waveguide Loop Couplers

The loop directional coupler is a well-known device that has been built in rectangular waveguide and coaxial transmission lines. However, loop couplers have not been previously constructed in circular waveguide. In 1946, Early[1] reported on a loop directional coupler for rectangular waveguide, and later, in 1956, Lombardini et. al.,[2] gave design criteria for loop couplers in rectangular waveguide and coaxial lines. The loop coupler reported herein draws on the fundamentals of previous authors and expands the design to the TM_{01} mode in circular waveguide at power levels in the hundreds of MW's range.

The present device consists of a section of circular waveguide attached to a side structure that contains the coupling loop. An aperture coupling the waveguide to the side structure can be either a round hole or an oval slot with the longer dimension of the slot parallel to the length of the circular guide. The largest dimension of the coupling aperture should be $\lambda_g/4$, where λ_g is the guide wavelength in the circular guide that corresponds to the center frequency of the device. The wall thickness of the coupling aperture should be small compared to a wavelength. The coupling aperture was epoxy filled with Torrseal to make a vacuum seal good to 1×10^{-6} torr. To avoid rf breakdown of the aperture, the epoxy surface on the interior of the waveguide was made very smooth. A cross-sectional view of the loop coupler is shown in Fig. 1.

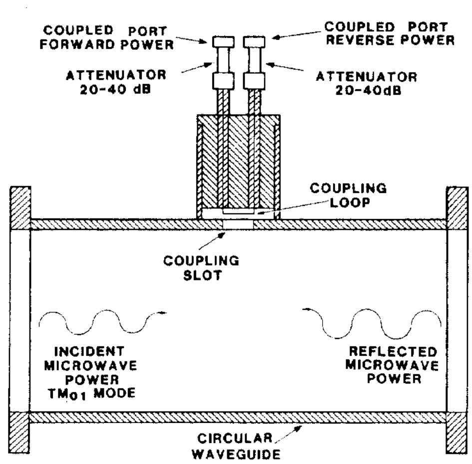

Figure 1. Cross-sectional view of loop coupler.

A TM_{01} mode propagating in the circular waveguide has field components E_z, E_r, and H_θ. E_z is zero at the wall of the guide, so the only field components which couple to the loop are E_r and H_θ. These field components leak through the slot and excite currents on the loop. Each end of the loop must be terminated or have enough attenuation to appear as a matched load to the signals propagating in the coax. The loop acts as a capacitive voltage divider, coupling to the passing electric field E_r and so gives rise to currents in both arms of the coaxial line in the same direction. The loop also couples inductively to the time rate of change of the magnetic field dH_θ/dt which excites currents in both arms of the coax in opposite directions.

This device is inherently a "backward" coupler. Power flowing forward in the main guide will be coupled to the loop and flow in the reverse direction in the coax; power flowing in the reverse direction in the main guide couples energy to the coax flowing in the forward direction.

Two loop couplers were constructed. The first operated in S-band with a bandwidth of 3.0 - 3.3 GHz, a coupling coefficient of 64 dB $\pm$ 0.5 dB, and a directivity of 15 dB. The second coupler operated in Ku-band with a bandwidth of 11.5 - 13.5 GHz, a coupling coefficient of 65 dB $\pm$ 1 dB, and a directivity of 13 - 16 dB.

Circular/Rectangular Waveguide Multihole Coupler

The circular/rectangular waveguide directional coupler operates in the TM_{01} mode in circular guide and couples to the rectangular waveguide TE_{10} mode. The phase velocities of waves traveling in both guides are matched in the region of the coupling slots. Since the circular waveguide is overmoded, the coupled rectangular guide must also be overmoded. Both guides must have the same cutoff frequency. The coupled rectangular guide tapers to standard size waveguide for the required operating frequency. In our experiments, WR-284 waveguide was used for S-band operation. A photograph of the coupler is shown in Figure 2. The overmoded rectangular waveguide section and both waveguide taper sections are 2.5 λ_g long each. A smooth taper transition is needed to ensure no mode conversion and small reflections.

Coupling slots connect the circular guide to the rectangular guide. These coupling slots are oriented at 45° with respect to the longitudinal dimension of the coupler. This orientation gives maximum coupling since the magnetic fields in the circular and rectangular waveguide are orthogonal. Any number of coupling slots two or greater can be used. In our coupler, three slots were chosen for simplicity and because a very high directivity was not needed. The coupling of the slots are made proportional to the coefficients of a Tchebycheff polynomial to improve the bandwidth of the coupler.

As in the loop coupler, the coupling slots were epoxy filled to make a vacuum seal. They were then covered with two layers of Eccosorb space cloth having

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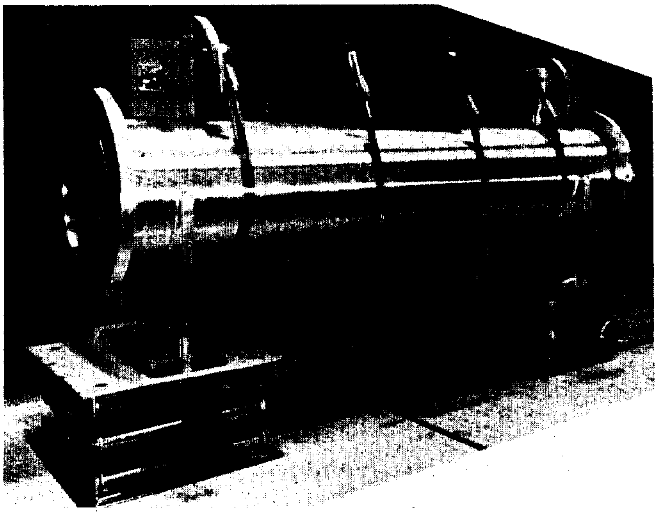

Figure 2. Photograph of circular/rectangular waveguide directional coupler.

a resistivity, R_s = 377 ohms per square. The walls of the rectangular waveguide near the coupling slots were also covered with the space cloth. This resistive cloth introduces loss which preferentially reduces unwanted modes from being generated in the overmoded rectangular guide. It also reduces reflections and, thus, helps to increase the directivity of the coupler. The cloth helps to increase the bandwidth and makes the coupling less sensitive to frequency.

The coupler was constructed for use on an S-band relativistic magnetron. It had an operational bandwidth of 2.9 - 3.4 GHz with a coupling coefficient of 63 dB $\pm$ 0.5 dB. The coupler was dual-directional, with a directivity that varied between 13 and 20 dB.

Circular Waveguide/Coaxial Multihole Coupler

The circular waveguide/coaxial multihole directional coupler is an original design device. The device couples the TM_{01} mode in circular waveguide to the TEM mode in a coaxial line. Both modes have similiar field patterns with E_r and H_θ field components. The TM_{01} mode has an E_z component, while the TEM mode is supported by a center conductor. The action of the center conductor is very similiar to that of the E_z field in the guide. Good coupling is achieved when the guide is overmoded and the coaxial line has a very low ϵ dielectric between the inner and outer conductor since both transmission lines then have phase velocities close to the speed of light. The coupling is produced by the E_r and H_θ field components. Figure 3 shows a cross-sectional view of the coupler. The bends in the coaxial line are only for convenience. They should be smooth, however, so that standing waves in the line are small. The wall thickness of the guide is reduced in the coupling region to about $\lambda_g/10$. A slot placed in the coax fits over the holes. The coupling of the holes was designed to be proportional to the coefficients of a Tchebycheff polynomial, which allowed a larger bandwidth than if all the holes had the same coupling. Six coupling holes were selected to provide a good directivity with a simple design. The coupler can measure both forward and reflected power in the guide. Our coupler had a coupling coefficient of 70 dB $\pm$ 1 dB over the frequency range 11.5 - 17.5 GHz. The directivity varied between 13 dB and 20 dB.

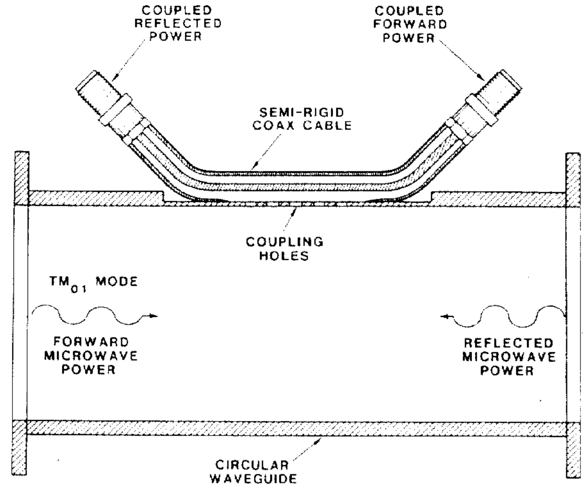

Figure 3. Cross-sectional view of circular waveguide/coaxial directional coupler.

Calibration

Two circular waveguide measurement systems were constructed to develop and calibrate directional couplers. One system uses 13.58 cm diameter waveguide for operation in S-band, while the other system uses 8.89 cm diameter waveguide for operation in Ku-band. Each system uses a TM_{01} mode launcher constructed from a tapered section of waveguide with an axial E-field probe at the narrow end. The narrow end of the taper was cutoff for modes higher than the TM_{01}. Thus, only the TE_{11} and the TM_{01} modes could propagate. The axial launching probe was adjusted to efficiently couple the TM_{01} mode to the coaxial line that supplied the calibration power. The mode launched was identified by propagating several watts of cw power and observing the heat pattern on a sheet of microwave absorbing liquid crystal material placed across the circular waveguide. Figure 4 shows the standard calibration system. The launchers in both systems had power transfer coefficients of 90%. The S-band system had a bandwidth of 2.6 - 3.8 GHz, and the Ku-band system had a bandwidth of 11.5 - 18 GHz.

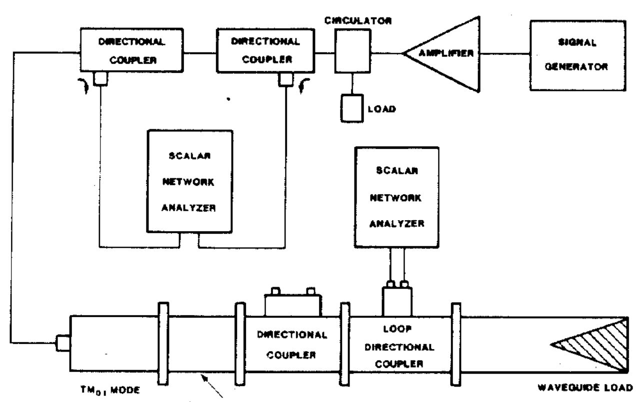

Figure 4. Experimental setup for coupler calibration.

The calibrations were performed in both a swept frequency mode using a scalar network analyzer and in a discrete frequency mode using power meters. The swept frequency measurements were performed first to ensure that the coupler had a smooth coupling response without resonances over the desired bandwidth. Next, the coupling coefficient was remeasured at many discrete points in the operating band. Directivity measurements were also performed in this manner. Many calibrations were performed with more than one coupler present in the system to provide cross calibration.

High Power Tests

The directional couplers described in this paper were used to measure the power generated by a relativistic magnetron[3] and a BWO.[4] The couplers measured both forward and reflected powers in the TM_{01} mode at levels of up to 300 MW. Figure 5 shows the waveguide system for the BWO incorporating a circular waveguide/coaxial coupler. An electron beam propagating through the slow wave structure generates microwaves that flow through the waveguide transition, into the coupler, and out the horn antenna. The BWO produces a single pulse 5 - 50 ns wide with a frequency of 12 - 16 GHz. The coupled power is further reduced by coaxial attenuators to about 100 mW. This power is measured by a point contact diode detector with a rise time of 2 ns. The diodes were calibrated at various frequencies for their voltage vs. power response. The detector voltage was measured with high bandwidth (400 MHz - 1 GHz) oscilloscopes. An overall accuracy of 1 dB is possible if all the attenuators are calibrated and the detector voltage is measured within 10 mV. EMP noise picked up by cables, and uncertainties in the frequency can reduce the accuracy of the power measurement.

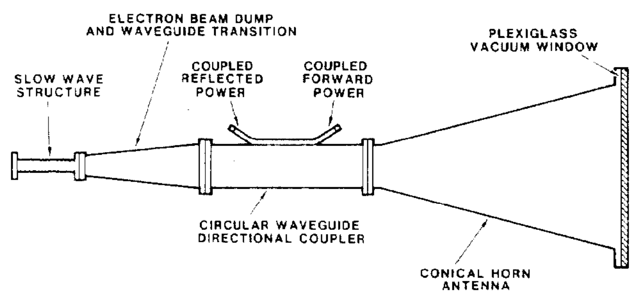

Figure 5. Experimental setup for high power BWO. Power is generated in slow wave structure and measured with the directional coupler.

Figure 6 shows a photograph of a loop directional coupler installed on the magnetron. The magnetron produces a 100 MW single pulse 50 ns wide at a microwave frequency of 3.15 GHz. The frequency is very stable, so a large bandwidth coupler is not required. The coupler measures both forward and reflected power flowing in the waveguide. The measurement of the power is very similiar to that used for the BWO. Coaxial attenuators reduce the coupled power, which is then measured by a fast diode detector. A high speed transient digitizer records the output voltage. The digitized voltage pulse is related to the high power flowing in the waveguide by the calibrations of the diode, attenuators, and the coupler. The stable operating frequency makes the overall system accuracy better for the magnetron.

Conclusion

Several new high power directional couplers for overmoded circular waveguide have been presented. These couplers were designed for use in the TM_{01} mode but could also be used for TM_{0n} modes. Large bandwidths and directivities are possible by using multihole couplers with large numbers of coupling holes. However, for very high power microwave sources, couplers with high directivities are not as important, since very accurate measurements are limited by single pulse repeatability and EMP noise. The couplers presented here were tested to power levels up to 300 MW. The maximum power limit is determined by the peak power and pulse duration necessary to breakdown the coupling holes.

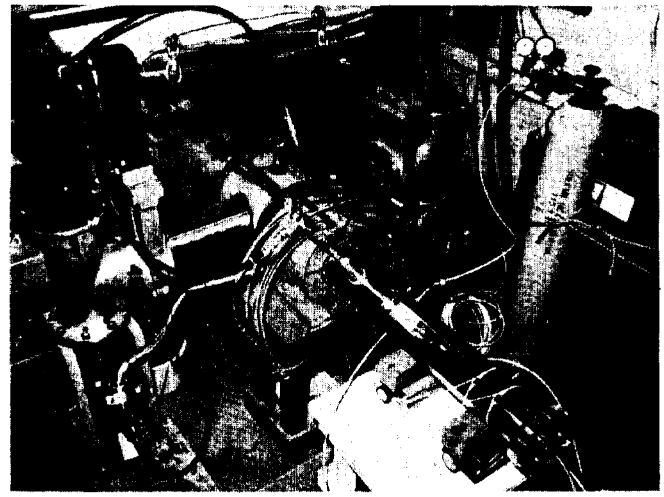

Figure 6. Photograph of high power magnetron with a loop coupler used to measure output power.

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