HIGH POWER MICROWAVE WINDOW DESIGN

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Abstract

The design of a heat-pipe cooled microwave waveguide window will be presented in this paper. The window is capable of handling megawatts of RF power in S-band (2.6 - 4.0 GHz) waveguide. The thickness and spacing of the windows, the window material characteristics, the thermal analysis of the heat pipe and the power handling capability will be addressed. The use of this technique in cooling other microwave components is discussed.

Introduction

Microwave considerations often limit the means available for cooling waveguide-mounted components, to the detriment of performance. In fact, in high power microwave windows, thermal cracking is the usual average power limitation. The problem is farther aggravated if the window is thin; heat conduction is along the long dimension of Figure 1a causing a maximum heat path length.

It would be much better if heat could be made to flow laterally along the short path, shown for our example in Figure 1b, and be removed directly from the faces of the heated areas.

This paper describes a way to remove the heat as desired, using the heat pipe principle in a unique manner to provide a cooling path that has an effective conductivity much greater than that of solid copper, but is at the same time microwave transparent. The design of a working model of a heat pipe cooled microwave window is discussed.

The Heat Pipe Principle

We start with a short explanation of the heat pipe principle. Consider the closed metal pipe shown in Figure 2. Bonded to its inner surface is a capillary material such as steel mesh or Fiberglas cloth, called the wick. To place the device in operation, one evacuates the structure, introduces enough of a suitable working fluid to saturate the wick, then seals the device. The heat pipe is now ready to operate, with the following simple cycle of operation.

Suppose one end of the pipe is heated, the other end cooled. Fluid will evaporate from the heated area. The resultant vapor will then travel to the cooled region and condense. By capillary action, the wick transports the condensed fluid back to the heated area, and the cycle repeats itself.

The temperature drop from the heated wall to the cooled wall can be quite small, on the order of two or three degrees Centigrade. It consists mostly of drops through the walls and wick/fluid/vapor space interfaces, plus small drops associated with vapor motion and capillary pumping losses. Even so, a small cross-section pipe can carry many thousands of kilowatts. The equivalent thermal conductivity can be a thousand times that of copper, yet the heat pipe is mostly empty space.

This last circumstance is a great convenience for microwave purposes, as is that fact that neither the walls nor the wick needs to be metallic (although good thermal conductivity is desirable). The fluid should also be a good microwave dielectric. It must, however, wet the wick and the surfaces to be cooled.

Figure 3 shows the high power microwave waveguide window in which the microwave transparent cooling technique is useful. In this application, the space between the two windows of a double wall window becomes the heat pipe. Wicking material is bonded to the inner surfaces of the windows and to the waveguide walls. Heat can then be removed directly from the inner faces of the windows, and deposited on the waveguide walls.

Since the microwave window is a simple structure, it was chosen to experimentally test the microwave transparent cooling technique. The remainder of the paper describes the design and performance of the experimental model.

Microwave Design Considerations

The thickness and spacing of the windows, the window material characteristics, and the maximum power handling capability of the window are of primary interest.

Thickness and Spacing of Windows

RF tests in both S and K_u band have been conducted on various window materials. Tests were conducted in S-band rectangular waveguide using 0.125-inch thick window having a dielectric constant of 3.3 made from slip-cast fused silica. These are thin windows with t/λ_g(dielectric) of 0.053 at 3 GHz. Swept frequency tests with the windows spaced 6.06 inches showed impedance matched conditions occurred for frequencies where the inner window faces were spaced n $\lambda_g/4$. The match frequency band centered at 3.17 GHz displayed a mid-band VSWR of 1.07 and a 2:1 VSWR bandwidth of 250 MHz.

Electrically thicker windows of 0.0625 and 0.125 inch thickness having ϵ_r = 2.6 and ϵ_r = 8.0 were tested in a circular waveguide having a diameter of 0.544 inches (cutoff frequency = 12.73 GHz). Tests were conducted in K_u band from 13 to 17 GHz. In this frequency range the windows can be classified electrically thick, with t/λ_g(dielectric) ranging from 0.12 (ϵ_r = 2.6 at 14 GHz) to 0.60 (ϵ_r = 8.0 at 17 GHz).

For these thick windows, best transmission characteristics were achieved when the spacing between inner window faces was n $\lambda_g/2$, for n an integer.

Window Material

The primary considerations for a window material are good thermal conductivity and very low RF loss factor. The characteristics of a number of organic and inorganic materials were compared and one of the materials that possesses both requirements was beryllium oxide. It has a thermal conductivity of 50 cal/cm-s $^{\circ}$C and a loss tangent much less than 0.001. These are compared to alumina whose thermal conductivity is 0.1 cal/cm-s $^{\circ}$C and loss tangent is also < 0.001. Thus, beryllium oxide does possess desirable properties for this particular application.

Power Handling Capability

Each window will absorb less than 0.1 percent of the incident power. Thus, in a one megawatt average power transmission system, each window would typically absorb less than one kilowatt of RF power. The heat pipe working fluid should then possess characteristics that would allow transparent cooling over the desired temperature range. The maximum power handling capability of this type device has not been fully determined since the effects of the reflections in the region between the windows have not been analyzed and the high voltage breakdown characteristics of the wick area have not been measured. Based on the heat pipe capacity to cool, the windows should operate in the 2-4 Megawatt average power range.

Thermal Design Considerations

Capillary Limitations

There are several factors which may limit heat transport through a heat pipe. These include boiling in the evaporator, vapor entrainment of liquid from the capillary structure, choking in the vapor region and maximum liquid flow in the capillary layer. Maximum capillary flow is the most important limitation in this application. As liquid flow increases in the capillary structure, pressure loss also increases. At the maximum flow rate, the pressure loss equals the maximum pressure rise furnished by the capillaries.

It is possible to affect capillary limitations considerably by changing the capillary configuration, by changing the working fluid, and by changing the operating temperatures. The temperature range of operation of the heat pipe is rather limited for a particular fluid. Thus to alter considerably the temperature level at the design point, different working fluids must be used. For example, a heat pipe designed for operation at 200°C will not function well at 400°C unless another working fluid is used.

Thermal Resistances

The most noteworthy feature of a heat pipe is its low thermal resistance. It is possible to make a heat pipe that has a thermal resistance which is orders of magnitude less than those of our best known conducting materials. Overall thermal resistance of a pipe is a sum of several resistances. These include resistances in the containing walls - in the present case the windows and waveguide, in the capillary structure plus working fluid at the evaporator and condenser, at the interface between liquid and vapor at both evaporator and condenser surfaces, and in the vapor region. The magnitude of the individual resistances is strongly a function of dimensions and thermal conductivity of the various materials. Generally it is desirable to have thin containment walls and thin layers of capillary material.

Selection of a Working Fluid

The choice of a working fluid is extremely important since heat pipes operate well only within a relatively narrow temperature range and of course in the present application we would like to use a fluid which has good microwave transmission characteristics. The fluid should have a vapor pressure near ambient pressure at the design operating temperature. In addition the fluid should have a large surface tension, a large heat of vaporization, a large liquid density, a small viscosity, transmit microwave signals well, and be chemically compatible with the window, capillary structure, and waveguide. It is also important for the fluid to have a relatively large thermal conductivity.

It has been determined that a reasonable temperature range for the working fluid in the present application is about 100 to 200°C. A number of fluids have been studied to determine if they might be suitable candidates for use in this heat pipe. Properties for some of these fluids will be presented.

It is clear from a study of the property data that water is a good heat pipe fluid from a thermal standpoint for the temperature range under consideration. Unfortunately water has very poor transmission properties for microwave signals. Considering both thermal and electrical properties, it appears that heptane may be a good choice for a working fluid.

Mechanical Design of Test Section

Sketches of the basic waveguide-cooling jacket sub-assembly and of the schematic of the complete test section are shown in Figures 4 and 5. The waveguide-cooling jacket sub-assembly is joined with a combination of silver and soft solder. The capillary structure is formed from 100 mesh copper screen along the waveguide and from fiber glass cloth on the windows at both ends. The working fluid cavity is sealed by an O-ring between the waveguide wall and the window on each end. A retaining collar is used to apply a force on each end of the complete assembly.

A test rig has been constructed which is used to measure thermal performance of the heat-pipe cooled microwave window. In this test section, microwave heating in the windows is simulated with resistance type heating. The heating coils are placed between two thin windows on each end of the heat pipe cavity.

Sufficient instrumentation is used to measure internal pressure, temperature distribution on the waveguide, heat transfer into the windows, and heat transfer into the condenser section (through the waveguide wall). A schematic of the test setup will be presented with this paper.

Test Results

The test section was assembled and only preliminary testing has been completed. The results, however, are quite encouraging. All testing to date has been carried out with water as the working fluid. In addition, all tests have been at relatively low power settings.

The power input to the device has, to date, been in a range between 50 and 250 watts. By using waveguide temperatures of about 60°F, it is possible to maintain vapor temperatures in the neighborhood of 70°F even at a heat flux of 250 watts. Thus the investigators expect that much higher power levels will be possible when vapor temperatures are allowed to increase to the 300 to 400°F range.

Axial temperature variations along the outside of the waveguide are quite small. Also, the internal pressure in the pipe is quite sensitive to changes either in input power or in cooling flow rate. This is important since it is an indication that thermal operation in this device can be controlled from either the evaporator or condenser areas.

Conclusions

A heat pipe cooled high power microwave window has been designed which will handle megawatts of average power. The choice of working fluid will depend on the RF power absorbed by each window, since there is an optimum temperature operating range for each fluid.

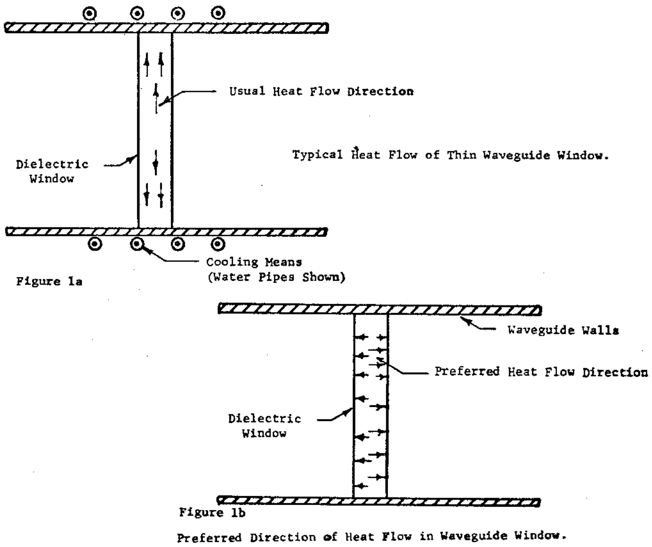

Fig. 1. Waveguide window.

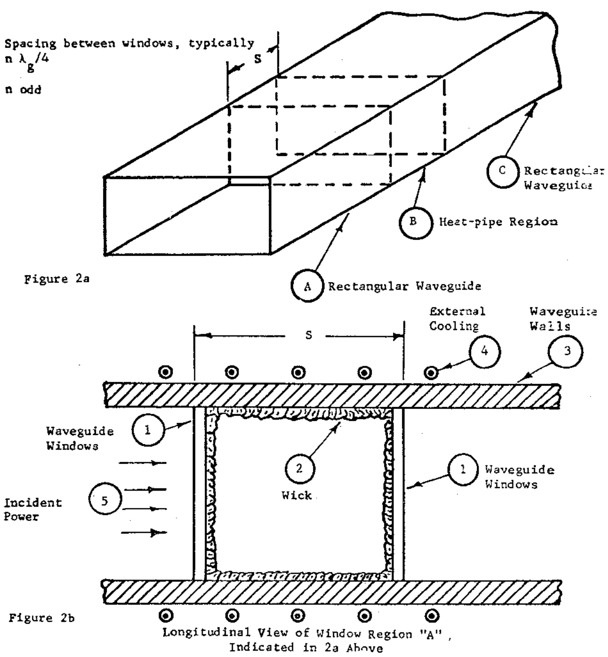

Fig. 3. Heat pipe cooled window.

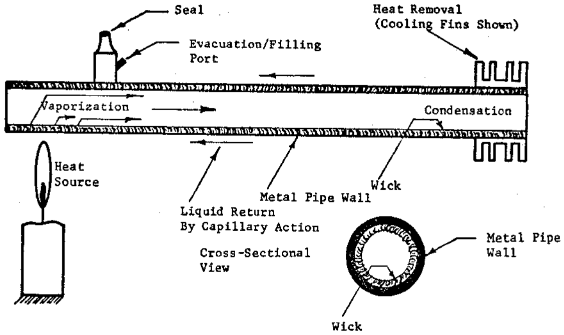

Fig. 2. Heat pipe operation.

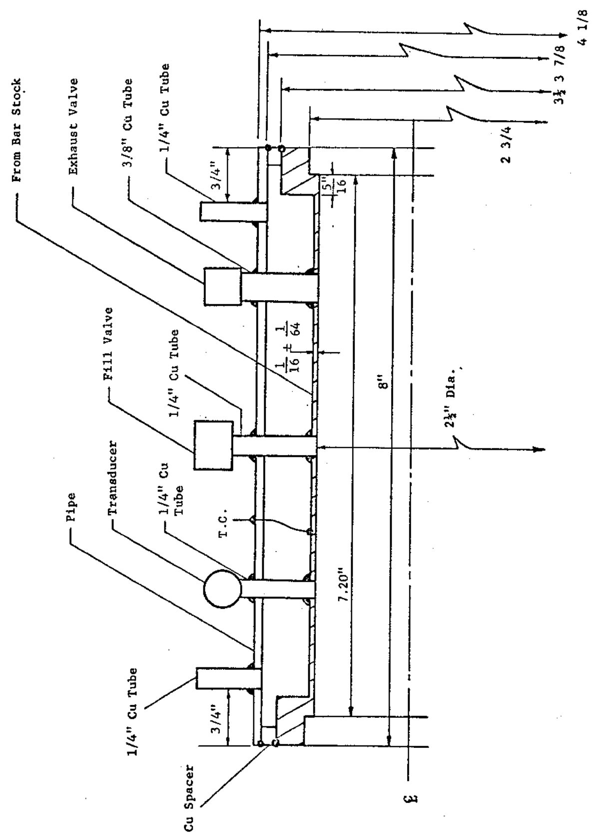

Fig. 4. Waveguide-cooling jacket.

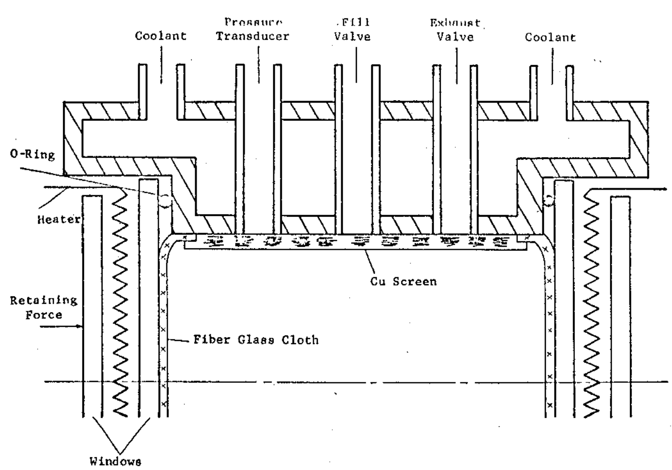

Fig. 5. Schematic of test section.

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