A 450-W Output Multiplexer for Direct Broadcasting Satellites

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Abstract—**The development and design of high power manifold type output multiplexers are described. The results obtained on Invar multiplexers with up to 450-W input power per channel are reported. The multiplexers are equipped with heat pipes in order to remove the heat generated in the filters.**

I. Introduction

A FEW YEARS AGO the development of an output multiplexer (OMUX) for a direct satellite-to-home broadcasting system was started within the framework of a German technology program called ZKS-II (Future Communication Satellites). The OMUX combines the TV channels coming from the TWTA's and feeds the antenna. In order to cover all envisaged applications, a maximum input power of 450 W per channel was assumed. The other requirements are identical to those of the planned German broadcasting satellite TV-SAT. According to this concept, five TV channels and one Telemetry (TM) channel are combined in the OMUX. More detailed specifications are given in Table I.

The center frequencies of the TV channels are located between 11.746 GHz and 12.053 GHz, whereas the center frequency of the TM channel is 12.499 GHz. The distances between the center frequencies of the TV channels are 76.72 MHz.

First of all, it was necessary to choose an appropriate concept for realization. After an evaluation of the different multiplexer concepts, it was decided to use a manifold type multiplexer in which bandpass filters for each channel are attached to a common waveguide.

The most critical parameters of such a multiplexer design are the distances between the filters on the manifold. They have to be determined by an optimization procedure. A new design procedure has, therefore, been developed which will be described briefly in Section II. The specification can be met with four-section Chebychev bandpass filters with an equiripple bandwidth of 34 MHz. In order to obtain the required rejection at the higher frequencies (above 15 GHz), low-pass filters are necessary.

The high input power levels entail a number of problems. It is of great importance to keep the losses in the filter as low as possible. The heat generated must be transported to a place from where it can be radiated into free space. This is achieved by means of heat pipes, which are attached to the filters. One main problem with the use of heat pipes is to provide a good thermal contact area and, hence, low thermal resistance between the device to be cooled and the heat pipe. In this context, it was necessary to calculate the heat distribution in the filters.

Since the OMUX has to be built in Invar—an alloy consisting of 65 percent Fe and 35 percent Ni—and the available heat pipes are made of aluminum, it is problematic to join the two materials for thermal expansion reasons.

It was also necessary to determine the maximum physical forces which could be tolerated by the OMUX without adversely affecting the electrical behavior. Investigations and tests were carried out concerning the occurrence of multipacting and the generation of intermodulation products.

TABLE I
SPECIFICATIONS FOR MULTIPLEXER CHANNELS

Insertion loss	≤ 0.8 dB
Return loss	> 23 dB
Bandwidth	≥ 27 MHz
Input power	450 W
Temperature	0°C...+90°C
Group delay variation	
at $f_0 \pm$ 6 MHz	± 0.5 ns
at $f_0 \pm$ 6.5 MHz	1.2 ns
at $f_0 \pm$ 10 MHz	2.25 ns
at $f_0 \pm$ 13.5 MHz	4.5 ns
Attenuation	
at $f_0 \pm$ 38 MHz	≥ 15 dB
at $f_0 \pm$ 62 MHz	≥ 35 dB
at $f_0 \pm$ 125 MHz	≥ 60 dB
7.8...f_0-200 MHz	≥ 70 dB
f_0+200...13.0 GHz	≥ 70 dB
17.3...24.4 GHz	≥ 60 dB
24.4...34.8 GHz	≥ 20 dB
34.8...36.6 GHz	≥ 60 dB

Manuscript received December 8, 1981; revised March 26, 1982. This work was supported in part by the BMFT (Ministry of Research and Technology) under Contract 01 YM 078-AK/KS-WRT 5040.

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0018-9480/82/0900-1317$00.75 ©1982 IEEE

As will be shown below, it was necessary for thermal reasons to use thick irises (2 mm and 4 mm) in the bandpass filters. Since no method of calculating the coupling coefficients of thick and large irises is known, the dimension of the coupling slots were determined experimentally according to [7].

II. Realization

A. Thermal Aspects

Different square and cylindrical resonator configurations which are operated in single and dual modes were evaluated with respect to their thermal and electrical behavior. As to the electrical performance, the TE_{113} dual-mode cylindrical resonators would have been the best solution. But a detailed analysis of the heat transfer from the filters to the heat pipes showed that for 450-W input power the coupling length provided by the filters in the TE_{113} dual-mode would have been too short. Therefore, we decided to use TE_{112} single-mode cylindrical cavities. This leads to slightly heavier filters with a sufficiently high unloaded Q.

To suppress unwanted spurious passbands, for instance, TE_{111} mode, we used resonators with three slightly different diameters between 23.5 mm and 24.5 mm.

Assuming a realizable Q-factor of 13 000, the dissipated heat in each bandpass filter is around 60 W. This figure and all others given below refer to an input power of 450 W. For the telemetry channel, TE_{112} dual-mode resonators are used, since its insertion loss is of minor importance.

In order to obtain the required rejection above 18.3 GHz, low-pass filters with 19 sections are necessary. They are designed according to Levy [6]. Their insertion loss was assumed to range between 0.1 and 0.2 dB which corresponds to a heat dissipation of around 20 W.

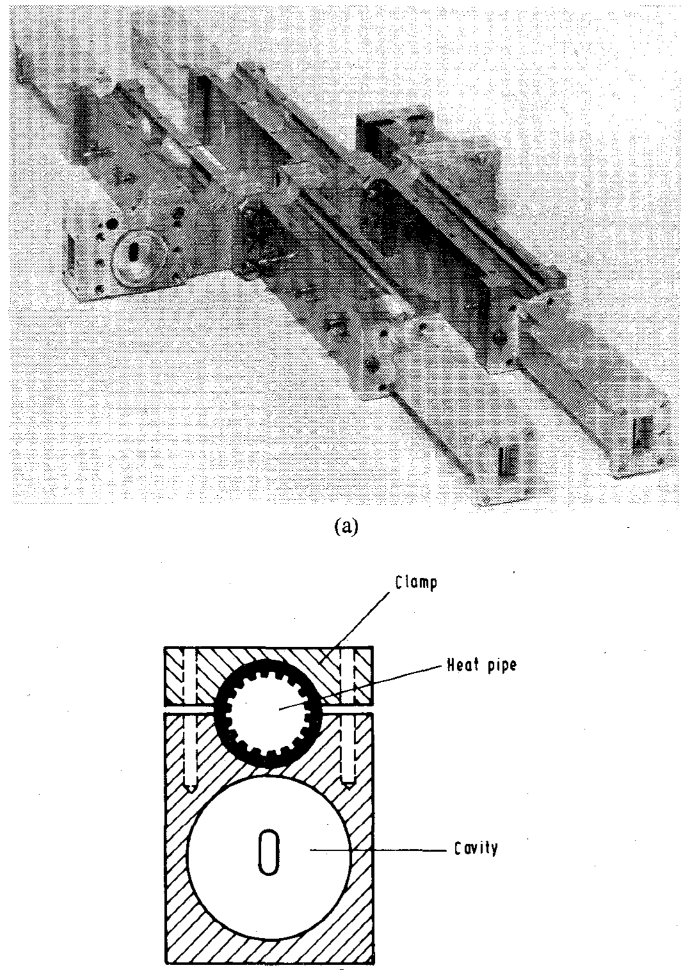
Therefore, a total heat of 80 W per TV channel is generated. Since the multiplexer is a compact device located in the interior of the satellite, this heat must be transferred to a location from where it can be radiated into free space. This is achieved by means of heat pipes, which are connected to the bandpass and low-pass filters.

Heat pipes are tubes closed at both ends and filled with a special medium which transports heat from a heat source and liberates it at a distant heat sink. This transportation is achieved with a very small temperature gradient and without any moving mechanical parts.

The principle of operation is based on the evaporation of a heat carrying medium (for instance NH_3) at the heat source, the transportation of the heat in the vapor state, and the liberation of the heat to a heat sink by condensation. The liquified-heat-conveying medium then returns to the evaporation zone by capillary action, which is supported by the special cross-section of the tubes (Fig. 1(b)).

In addition to the electrical, thermal, and mechanical problems, several technological difficulties in designing and manufacturing such an OMUX in Invar had to be overcome.

As mentioned above, we will, to some extent, explain the design procedure in Section II. In Section III we will describe how the OMUX was realized. Section IV will discuss the tests carried out on two multiplexers, one with six channels and one with two channels (a diplexer). Finally, in Section V, we will present our conclusions.



(a)

(b)

Fig. 1 (a) Invar OMUX with low-pass filters. (b) Filter-heat-pipe configuration (cross section).

III. Design Procedure

One aim of the theoretical work was to establish a general design procedure for the manifold multiplexer (Fig. 2). If the guardband is sufficiently large then—in the design of one partial filter—the input impedances of all other partial filters may be taken as nearly frequency independent. It is possible to use doubly terminated filters and to vary only the distances between the filters (l_m) in order to obtain the desired performance [1]. If the channel separation becomes smaller, then the input impedances are no longer frequency independent and the filter elements have to be included in the optimization process [2]–[4]. This leads eventually to a drastic increase in the number of optimization parameters and entails a tedious optimization procedure. This can be avoided if the solution of the problem is reduced to the iterative application of the well-known and proven methods of filter synthesis.

In designing one partial filter it is possible to show that

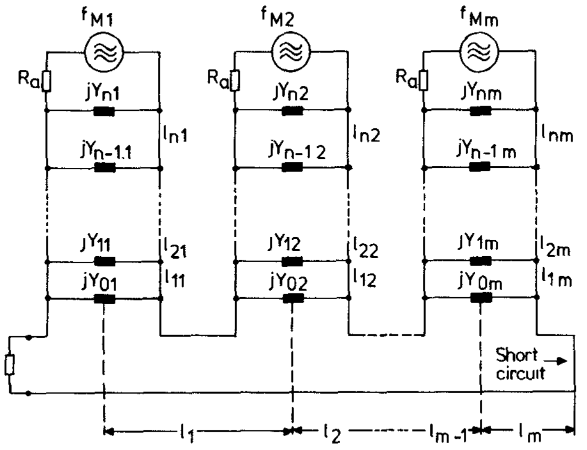


Fig. 2. Equivalent circuit of a manifold multiplexer.

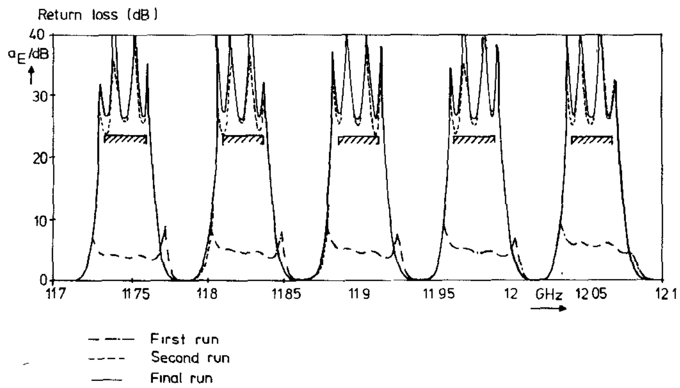


Fig. 3. Calculated return loss of an optimized output multiplexer.

the impedances of the other partial filters can finally be represented by a series resonance circuit [5]. Transformation to a low-pass means that a reference low-pass has to be synthesized which is doubly terminated but starts with a series inductance at the manifold side. This can be achieved by designing a so-called parametric filter, i.e., a filter which contains an additional real zero and is one degree higher than the partial filter. It is better to start the multiplexer design with the filter which is near the short circuit and to proceed until the filter at the common output is reached. It is unlikely that the desired performance will be obtained after the first run since every newly designed partial filter influences the performance of all others. So far only a few runs were required in order to obtain satisfactory results.

Fig. 3 shows the results of the application of the design procedure for the problem at hand. The telemetry channel is not shown. It can be seen that only three runs were necessary to be well within the specified values. A more detailed description is given in [5]. This procedure provides the distances between the bandpass filters and the normalized low-pass prototype elements of these bandpass filters. In the course of realizing multiplexers, it turned out to be advisable to arrange the filters in such a way that the channel with the lowest center frequency is at the common output followed by the other channels ascending in center frequencies. But different arrangements are also possible.

Calculations of the heat distribution in the bandpass filters have shown that approximately 66 percent of the heat is produced in the resonator and 34 percent is generated in the irises. In order to minimize the shift of the center frequencies of the bandpass filters with temperature, they have to be made of Invar. Using the above quoted values it was found that it is not possible to use Invar irises, since the temperature rise at the inner irises would be around 200°C, when the main body is kept at 65°C. It was, therefore, decided to use thick irises made of pure silver, which has a thermal conductivity 40 times better than Invar. In this way, the temperature rise is restricted to a few degrees. Whereas, for thermal reasons, a thickness of 1 mm would be sufficient, we used 4-mm thickness in order to enable the incorporation of a thread for a coupling tuning screw.

The 450-W multiplexer is shown in Fig. 1(a). One bandpass filter is detached. In the 450-W version, heat pipes were clamped into grooves, which were milled into the bandpass filters (Fig. 1(b)). This was done in order to optimize the heat transfer between filters and heat pipes.

A. *Multipacting*

According to Clancy [8], who investigated the phenomenon of multipacting, a potential multipactor risk exists for microwave components handling power levels above 4 W and having gaps with *fd* products between 0.6 GHz·mm and 40 GHz·mm. Here *d* is the gap width in millimeters and *f* is the operating frequency in gigahertz.

Since all calculations concerning the multipacting are not very reliable, one cannot proceed without tests. In the case of filters with high *Q* resonators, the occurrence of multipacting can be seen by a sudden deterioration of the return loss. High power tests described in Section IV-B showed that multipacting does not occur.

B. *Technological Aspects*

As explained above, the bandpass filters and the common waveguide were made of Invar, whereas the irises in the bandpass filters consist of pure silver. In order to provide the required mechanical stability and the lowest thermal resistance, the bandpass filters had to be brazed. It seemed to be impractical to braze the whole OMUX in one piece. It was, therefore, decided to braze the low-pass, bandpass filters and the common mainfold separately and to screw them together. The brazing of two materials with such different properties led to some problems. For instance, a considerable change was observed in dimensions of the coupling slots. It can be explained as follows.

Due to the different thermal expansion coefficients of silver and Invar, the change of dimensions is also different with increasing temperature. When the filters are cooled after brazing, different shrinkage occurs, i.e., the silver irises are kept under high tension by the surrounding Invar and the coupling slots are widened. Since the amount of this change cannot be predicted exactly, it is necessary to have tunable couplings.

The coupling slots in the common manifold cannot be tuned, but the irises are accessible after brazing and the slots were therefore milled into the irises after brazing. In this way they can be given sufficiently exact dimensions.

IV. Test Results

Using the procedures described above, one six-channel multiplexer for 450-W input power and one diplexer for 280-W input power have been manufactured and thoroughly tested with low and high input power.

A. Low Power Tests

The bandpass filters are first tuned on a separate tuning fixture and then screwed to the common guide. After assembly, only minor tuning is required to obtain the desired performance, if the channels are arranged properly as mentioned in Section II.

Fig. 4 shows the return loss measured at the common guide. As can be seen, the return loss for the TV channels is better than 26 dB. For the TM channel—centered at 12.49 GHz—which has a usable bandwidth of only 1.2 MHz, a return loss of 20 dB was required.

The insertion loss measured in one channel, including the low-pass filter, is shown in Fig. 5. In all other channels, the measured insertion loss ranged between 0.58 dB and 0.63 dB. These values have been obtained at room temperature. If the filters are heated to 90°C (as required in the qualification test) an increase of 0.1 dB is observed. The out-of-band rejection and the return loss, measured in one channel, are shown in Fig. 6.

The far out-of-band rejection has been measured in the range from 8 GHz up to 36.6 GHz. The attenuation was as specified in Table I. In order to obtain the required rejection above the filter passbands, we used low-pass filters with reduced width. In this way, we obtained an excellent performance up to the third harmonics and a excellent return loss (26 dB) without tuning.

B. High Power Tests

The high power tests were performed using a six-channel OMUX and a diplexer at 450-W and 280-W input power in a vacuum chamber. The six-channel multiplexer was equipped with heat pipes which were cooled outside the chamber by liquid nitrogen (Fig. 7). During the diplexer tests, the heat pipes were simulated by an Al-plate which was cooled by a Cu-plate equipped with cooling tubes.

In this way, temperature of the test object could be controlled to any desired temperature. We performed measurements mostly in the qualification range, i.e., between 20°C and 90°C. During the tests, the temperatures were recorded at several points of the OMUX.

Fig. 8 shows how the insertion loss changes with increasing temperature if 450 W are applied. The difference in the loss (1.13 dB) compared to the value measured at low power (0.6 dB), is caused by the test setup. In all these measurements, the increase never surpassed 0.1 dB, even within the temperature range of 20°C to 90°C. This value is also roughly obtained if one takes into account the increase of the surface resistance of Ag with temperature in the calculation of the unloaded Q.

Fig. 9 shows the change of return loss under the same

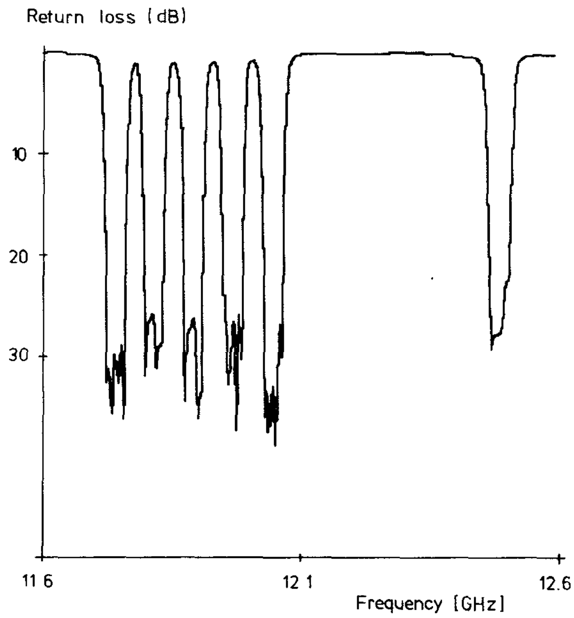


Fig. 4. Measured return loss into the common waveguide.

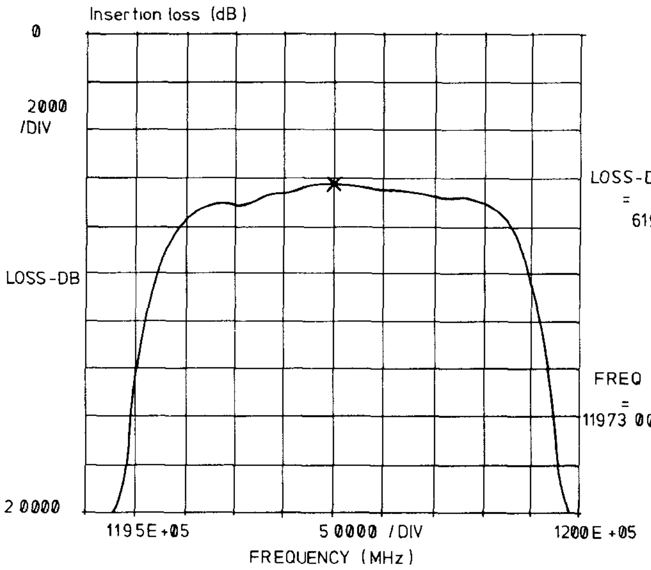


Fig. 5. Measured insertion loss of one channel including low-pass filter.

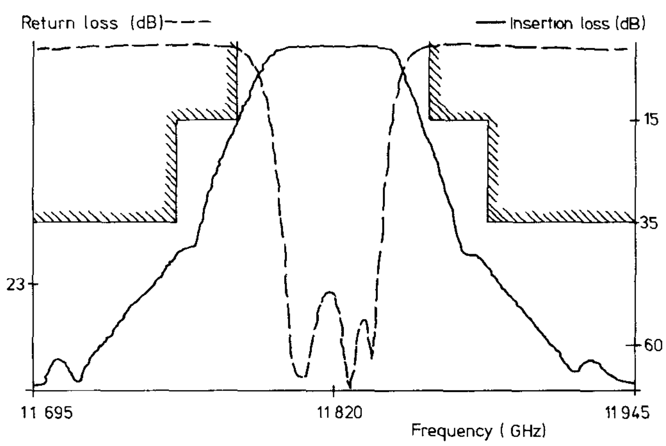


Fig. 6. Return loss and near out of band attenuation, measured into one channel.

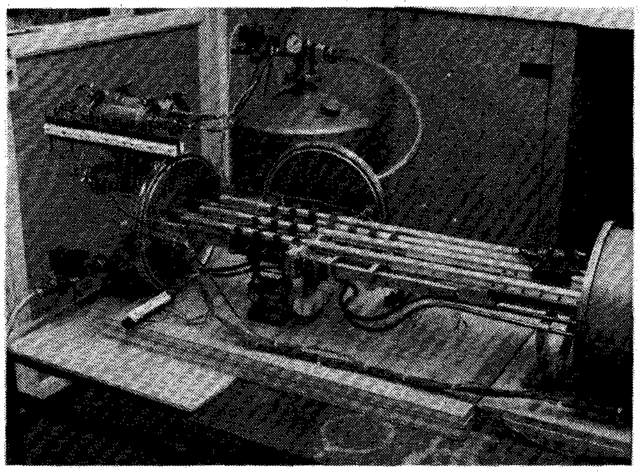


Fig. 7. Six-channel OMUX with heat pipes ready for insertion into the vacuum chamber.

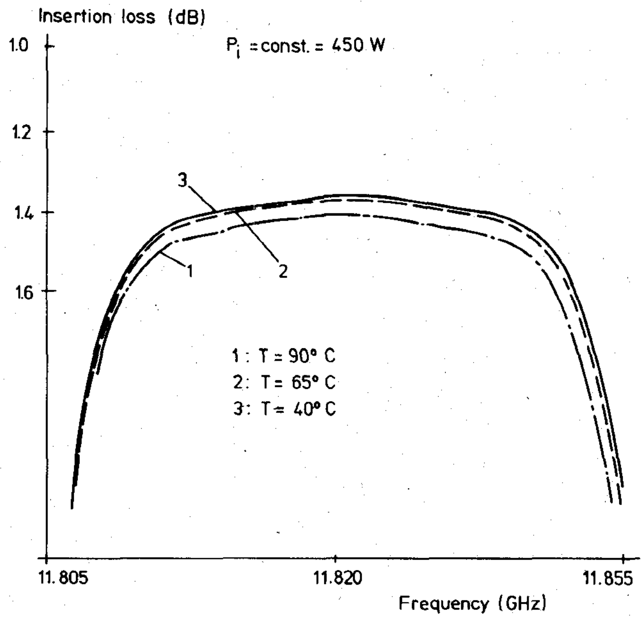


Fig. 8. Insertion loss measured at different OMUX temperatures with 450-W input power.

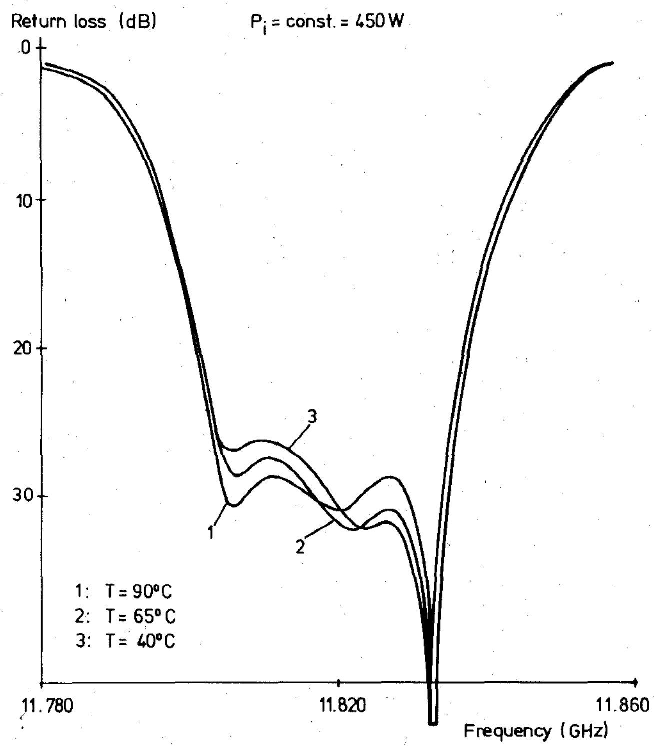


Fig. 9. Return loss measured at different OMUX temperatures with 450-W input power.

conditions as described above. A change occurs mainly in the shape of the curves. Another interesting feature can also be seen at the center frequency which moves to a higher frequency instead of to a lower one as would be expected. This "overcompensation" can be explained by the use of thick Ag irises.

The measurements shown in Figs. 10 and 11 were obtained with the diplexer having an input power of 230 W. In these tests, high power was applied to both channels. From these and similar tests performed with the six-channel OMUX, we discovered that the individual channels are almost completely thermally decoupled. A further result is that, at all points monitored, the temperature increased only a few degrees over the reference level, which was selected at the test object very close to a heat pipe.

With a simple test setup—using the Omux and only one additional bandpass filter—we checked the device for intermodulation products (IMP). With an input power of 200

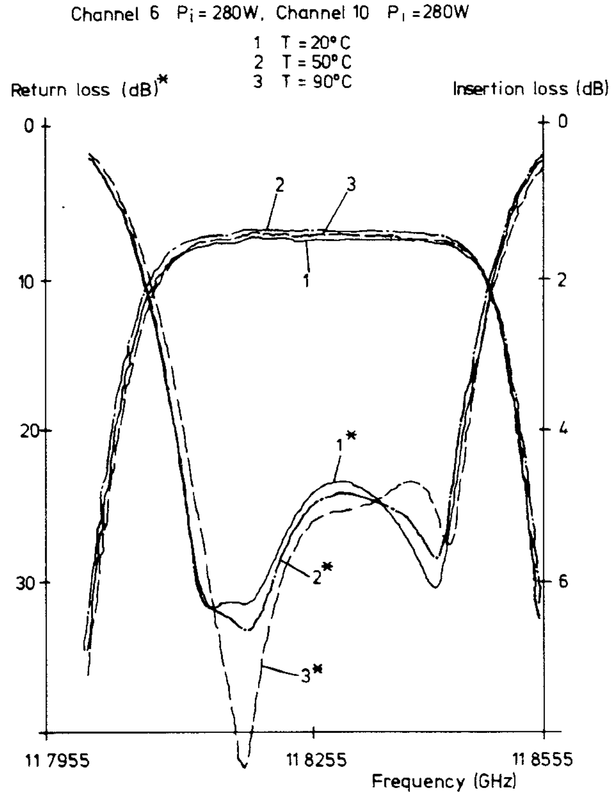


Fig. 10. Return loss and near out-of-band attenuation at different temperatures with 2 times 280-W input power.

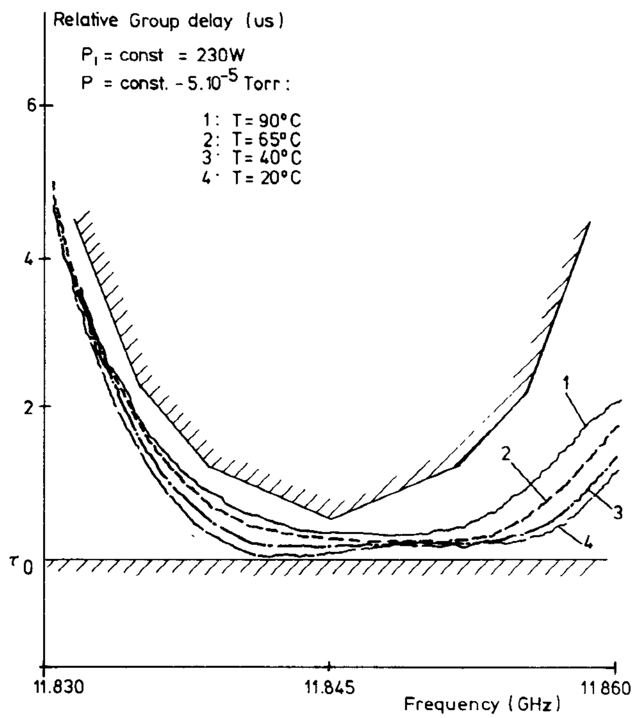


Fig. 11. Group delay of one channel at different temperatures.

W, the levels for the IMP's of third and fifth order were less than −70 dBm and less than −90 dBm, respectively. It is very likely that these IMP's were caused by the absorber or by the flanges of an interconnecting waveguide piece. The output flange of the OMUX has been modified in order to increase the contact pressure.

V. Summary and Conclusions

The main problems arising in the development and design of manifold type multiplexers have been described and explained, including possible solutions.

At high input power levels above 150 W, heat pipes must be used in order to remove the heat generated in the filters by ohmic losses.

The bandpass filters have to be made of Invar in order to minimize the shift of the center frequencies with temperature. But it is advisable to use a different material for the irises to quickly transport the heat to the walls. Invar has a very poor thermal conductivity, which is only 1/40 of that of Ag.

It was shown that the concept developed is suitable for application in high power broadcasting satellites.

Acknowledgment

The authors thank Dr. G. Müller for his support in establishing the procedure and computer program for the design of manifold multiplexers.

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