Cryogenic Millimeter-Wave Ring Filter for Space Application

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***Abstract*—A tunerless cryogenic millimeter-wave ring filter has been designed for a space application. Detuning of the center frequency caused by thermal deformations has been compensated by a novel mechanism based on the use of two materials with different temperature expansion coefficients. An improvement of 1 : 8 in the detuning of the center frequency, compared to an uncompensated ring filter, is reported. By applying the new design, external tuning aids can be avoided even in applications where a wide operational temperature range is of interest. Thus, the new ring filter is especially advantageous in space-borne millimeter-wave receivers.**

***Index Terms*—Diplexer, ring filter, space application, temperature compensation.**

I. Introduction

RING FILTERS based on the resonance properties of ring circuits [1] are commonly used as diplexers in millimeter-wave receiver front-ends for combining the radio frequency (RF) and local oscillator (LO) signals for a mixer [2]. Fig. 1 shows a simple application. In addition to the isolation between the LO and RF ports, the ring filter rejects LO noise at the receiving frequency and, thus, reduces the receiver noise.

At millimeter-wave frequencies, the ring filter is often made of rectangular waveguides milled into metal block. In cryogenically cooled receivers, all front-end parts, including the ring filter, are cooled down to some temperature between 4–100 K. When cooled, due to the nonzero thermal expansion coefficient of the block material, the mechanical dimensions, i.e., the length of the ring and the cross section of the waveguide, will change. These thermal deformations, in turn, change the group wavelength λ_g and the electrical length of the ring resonator. Consequently, the center frequency of the passband is shifted, the LO signal experiences excessive losses, and the mixer may suffer from reduced LO power if no tuning is accomplished after the cooling or warming action. The need for wide temperature range operation is twofold; in space-borne systems, operation of a receiver, though degraded, should be maintained after a possible failure in the cooling system. Moreover, the overall functional tests carried out on the ground at room temperature prior to launch become easier and safer.

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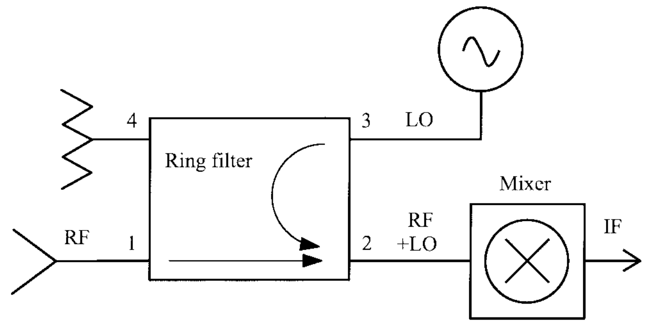

Fig. 1. Application of ring filter as an RF–LO diplexer in a millimeter-wave receiver.

Because the 3-dB passband and detuning of an uncompensated ring filter are both typically of the order of 0.3% of the center frequency, an excessive loss of several decibels will occur when the ring-filter temperature is changed between room temperature and normal operating temperature. Small changes in ambient temperature also cause larger center frequency shifts, which may be troublesome in some applications. Normally, mechanical tuning aids are required to compensate for this detuning effect every time the temperature is changed. In ground-based systems, tuning can be performed manually. However, in space-borne systems, mechanical tuning systems based, for example, on motors, should be avoided since they are expensive and risky with respect to the mission reliability.

In this paper, we introduce a tunerless ring filter with a temperature compensation mechanism that keeps the center frequency practically constant regardless of temperature variations. We present the mechanical structure of the ring filter, design a formula for achieving the proper compensation, and finally, compare the theoretical and experimental results of a ring filter designed for a 119-GHz millimeter-wave receiver on board the Swedish Odin space telescope [3].

II. Ring Filter as RF–LO Diplexer

A ring filter comprises two transmission lines that are connected by a ring transmission line and two directional couplers $C1$ and $C2$ (see Fig. 2). This four-port acts as a frequency-dependent directional coupler whose coupling between ports 1 and 4 and between ports 2 and 3 has maximums at the resonant frequencies of the ring. A signal experiences low loss from port 1 to 2 and from port 3 to 4. At the resonant frequency S_{23}, transmission from port 3 to 2 can be written [4]

$$S_{23} = \frac{c^2 e^{-\alpha l/2}}{1-(1-c^2)e^{-\alpha l}} \tag{1}$$

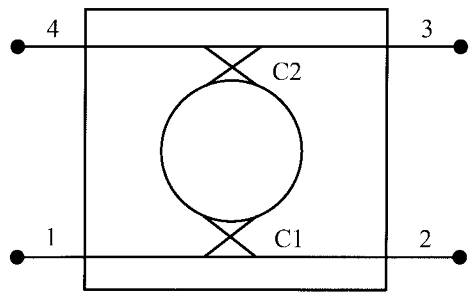

Fig. 2. Schematic diagram of ring filter.

where c is the coupling of the directional couplers $C1$ and $C2$, l is the length, and α is the attenuation in nepers per unit length of the ring transmission line. At other frequencies, which correspond to the electrical length around the loop equal to $n2\pi + \theta$, $(n \in N)$, S_{23} becomes [4]

$$S_{23} = \frac{c^2 e^{-(\alpha l + j\theta)/2}}{1 - (1 - c^2) e^{-(\alpha l + j\theta)}}. \quad (2)$$

Use of (1) and (2) assumes that all transmission lines have equal characteristic impedance, and the directional couplers $C1$ and $C2$ are matched and have infinite directivity.

Let us assume a generator that launches a wave to port 3. As the wave travels toward port 4, a portion of it is coupled to the ring via coupler $C2$. Assuming $C2$ is ideal and port 4 is matched, a wave traveling in only one direction is launched into the ring. At the resonant frequency f_c, the wave entering into the ring combines in phase with the wave already propagating in the ring and the field reaches its maximum. Consequently, the power coupled to port 2 via directional coupler $C1$ reaches its maximum value at f_c. No power is coupled to port 1, i.e., ports 1 and 3 are isolated, providing the isolation needed between the RF and LO ports. At frequencies sufficiently far away from f_c, $|S_{23}|$ becomes small, providing attenuation for the unwanted noise components emanating from the LO. For optimum filtering, the minimum of $|S_{23}|$ should appear at the RF and image frequencies, which minimizes the receiver noise.

At millimeter-wave frequencies, it is practical to construct the ring filter of rectangular waveguide and sidewall couplers operating at the fundamental TE_{10} mode [2]. The ring waveguide is cut along the center line of the broad side (E-plane) and, thus, it consists of two blocks. It is well known that a small gap in the middle of the broad side does not disturb the TE_{10} mode. This facilitates tuning of the center frequency by adjusting the gap width. A cross-sectional view of this kind of a waveguide structure is shown in Fig. 3. As the gap is kept small, the standard equations for the rectangular waveguide can be applied to a sufficient accuracy.

The group wavelength λ_g for the TE_{10} mode is

$$\lambda_g = \frac{c_0}{\sqrt{f^2 - \frac{c_0^2}{4a^2}}} \quad (3)$$

where c_0 is the speed of light, f the frequency, and a the broadside width of the waveguide. For the ring waveguide, θ

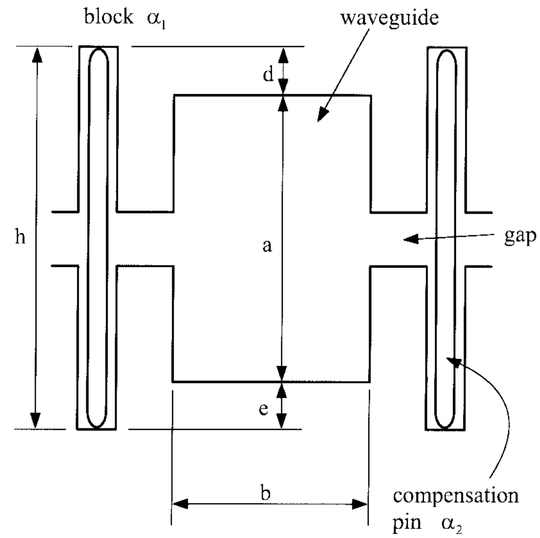

Fig. 3. Cross-sectional view of ring resonator waveguide and principle of temperature compensation mechanism.

in (2) then becomes

$$\theta = \frac{2\pi l}{\lambda_g} - n2\pi = \frac{2\pi l}{c_0}\sqrt{f^2 - \frac{c_0^2}{4a^2}} - n2\pi \quad (4)$$

where l has to be a multiple n of the group wavelength λ_{gc} at f_c

$$l = n\lambda_{gc}. \quad (5)$$

n is selected so that θ is close to π and, thus, $|S_{23}|$ is close to minimum at the RF-band center frequency f_{rf} and at the image-band center frequency f_{im}.

III. Effect of Temperature

Due to the nonzero thermal expansion coefficient, the mechanical dimensions change as the temperature of a ring-filter block is varied. Accordingly, the ring length l and the waveguide width a are also functions of temperature. These parameters affect the phase θ in (4).

Let us first consider a filter that consists of a single material and has a thermal expansion coefficient[1] α_t. We then have for l and a

$$l = l_0[1 + \alpha_t(T - T_{\mathrm{ref}})] \quad (6)$$

$$a = a_0[1 + \alpha_t(T - T_{\mathrm{ref}})] \quad (7)$$

where l_0 and a_0 are the nominal values for l and a, respectively, at the reference temperature T_{ref} and T is the physical filter temperature. By substituting (6) and (7) in (4) and differentiating, we obtain

$$\frac{d\theta}{dT} = \frac{\alpha_t l_0 \pi}{c_0}\sqrt{4f^2 - \frac{c_0^2}{a_0^2[1 + \alpha_t(T - T_{\mathrm{ref}})]^2}} + \frac{\alpha_t c_0 l_0 \pi}{a_0^2[1 + \alpha_t(T - T_{\mathrm{ref}})]^2} \cdot \left(\sqrt{4f^2 - \frac{c_0^2}{a_0^2[1 + \alpha_t(T - T_{\mathrm{ref}})]^2}}\right)^{-1}. \quad (8)$$

[1] The coefficient is generally a function of temperature, but for simplicity, we assume the coefficient to be constant over the temperature range of interest.

Above the cutoff frequency, the square-root terms are always positive. Therefore, the sign of (8) only depends on the sign of α_t, and $d\theta/dT$ cannot reach zero for any nonzero α_t. Thus, we conclude that in a single-material filter, the change of the center frequency as a function of temperature is inevitable.

IV. Temperature Compensation

In order to overcome the limitation pointed out by (8), we introduce a ring-filter mechanism, which consists of two different materials having different temperature expansion coefficients α_1 and α_2. This will give us a possibility of controlling $a(T)$ and $l(T)$ at a different rate. It will be shown that by selecting the mechanical dimensions of the two materials properly, $d\theta/dT$ can be zeroed at the reference temperature T_{ref}. The principle of the compensation structure is presented in Fig. 3. Using the illustrated definitions, we can write

$$h = h_0[1+\alpha_2(T-T_{\text{ref}})] \quad (9)$$

$$d = d_0[1+\alpha_1(T-T_{\text{ref}})] \quad (10)$$

$$e = e_0[1+\alpha_1(T-T_{\text{ref}})] \quad (11)$$

where d and e are the lengths by which the compensation pin length h exceeds the waveguide wall planes at each end. h_0 is the length of the compensation pin at the reference temperature T_{ref}. The broadside dimension a can be written

$$a = h-(d+e) \quad (12)$$

$$a = [h_0\alpha_2-(d_0+e_0)\alpha_1](T-T_{\text{ref}})-(d_0+e_0)+h_0 \quad (13)$$

$$a = [h_0\alpha_2-(h_0-a_0)\alpha_1](T-T_{\text{ref}})+a_0. \quad (14)$$

The length of the ring is

$$l = l_0[1+\alpha_1(T-T_{\text{ref}})]. \quad (15)$$

By substituting (14) and (15) in (4) and differentiating, with respect to T, we obtain the rate of phase for the double-material filter, shown in (16), at the bottom of this page. Because there is no limitation for selecting T_{ref}, we can set $T=T_{\text{ref}}$ without losing generality. It follows that

$$\frac{d\theta}{dT} = \frac{\alpha_1 l_0\pi}{c_o}\sqrt{4f^2-\frac{c_0^2}{a_0^2}}+\frac{c_0 l_0\pi[\alpha_1(a_0-h_0)+\alpha_2 h_0]}{a_0^3} \cdot\left(\sqrt{4f^2-\frac{c_0^2}{a_0^2}}\right)^{-1}. \quad (17)$$

Finally, by setting $d\theta/dT=0$ in (17), we can solve for the required pin length h_0 for the optimum compensation action at T_{ref}. We obtain

$$h_0 = \frac{4a_0^3 f^2}{c_0^2\left(1-\dfrac{\alpha_2}{\alpha_1}\right)} = \frac{4a_0^3}{\lambda_0^2\left(1-\dfrac{\alpha_2}{\alpha_1}\right)} \quad (18)$$

where λ_0 is the free-space wavelength at frequency f equal to f_c. However, if α_1 and α_2 change with temperature, we may expect that the ratio α_2/α_1 is maintained unchanged to a better degree. It is interesting to note from (18) that the dimensions of the compensation mechanism do not depend on n or l.

V. Ring Filter for 119-GHz Receiver

The temperature-compensation mechanism was applied to a ring filter designed for a 119-GHz molecular oxygen line receiver in the Swedish Odin satellite [3] to be used for astronomical and aeronomical research.

The ring filter combines an LO signal at a frequency of either 114.750 or 114.850 GHz and an RF signal of 118.250–119.250 GHz for a Schottky diode mixer [5], [6] and provides isolation between the RF and LO ports. During the mission, the receiver front-end will operate in vacuum at a temperature range from 100 to 120 K. However, during tests, the receiver should be capable of operation at temperatures around 295 K. For any usable ring-filter block material, the temperature expansion coefficient would have been prohibitively large in order to achieve detuning of the center frequency small enough at the specified temperature range from 100 to 295 K. If tuned for optimum performance at 100 K, a serious detuning would have occurred at 295 K and caused an excessive power loss of approximately 5 dB, which would have spoiled the performance of the receiver at the higher temperature. In order to facilitate a tunerless operation over a wide temperature range, the presented temperature compensation mechanism was utilized.

The structure of the filter is shown in Figs. 4 and 5. The WR-8 input waveguides are made, using split block techniques, into block I (bottom) and II (center). The ring resonator is also of WR-8 waveguide type and is milled symmetrically in blocks II and III (uppermost), which are separated by the temperature compensation pins. The two-directional sidewall couplers consist of six oval holes. The wall thickness is 0.1 mm, which provides a coupling of about 14 dB according to simulations. Smoothly sliding dowel pins are used for increasing the alignment accuracy of block III. Four screws and their associated springs hold block III firmly pressed against the compensation pins. The remaining air gap between the blocks is nominally 50 μm and varies about 10 μm within the specified temperature range.

The block is made of gold-plated brass and the compensation pins are of stainless steel, type 100Cr6, for which the

$$\frac{d\theta}{dT} = \frac{\alpha_1 l_0\pi}{c_o}\sqrt{4f^2-\frac{c_0^2}{[a_0+(\alpha_1(a_0-h_0)+\alpha_2 h_0)(T-T_{\text{ref}})]^2}}+\frac{c_0 l_0\pi[\alpha_1(a_0-h_0)+\alpha_2 h_0][1+\alpha_1(T-T_{\text{ref}})]}{[a_0+(\alpha_1(a_0-h_0)+\alpha_2 h_0)(T-T_{\text{ref}})]^3} \cdot\left(\sqrt{4f^2-\frac{c_0^2}{[a_0+(\alpha_1(a_0-h_0)+\alpha_2 h_0)(T-T_{\text{ref}})]^2}}\right)^{-1} \quad (16)$$

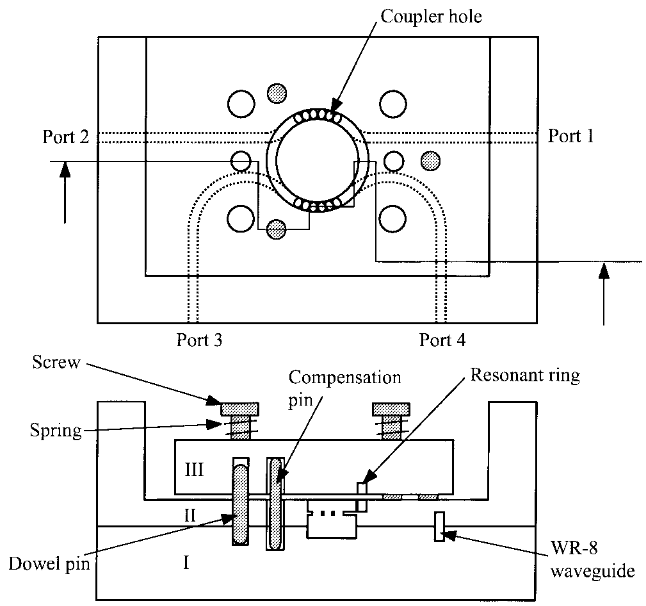

Fig. 4. Structure of ring filter for 119-GHz Odin receiver.

Fig. 5. Photograph of prototype filter. Port 2 (WR-8 waveguide) is seen on the left side and ports 3 and 4 on the right side.

temperature expansion coefficients are $\alpha_1 = 19 \cdot 10^{-6}$ K^{-1} and $\alpha_2 = 11.5 \cdot 10^{-6}$ K^{-1}, respectively. By substituting α_1, α_2, $a_0 = 2.032$ mm, and $f = 114.800$ GHz[2] into (18), we obtain $h_0 = 12.4665$ mm.

From (4) and (5), we obtain f as a function of phase θ

$$f = \sqrt{\left[\frac{c_0(\theta + n2\pi)}{n2\pi\lambda_{gc}}\right]^2 + \frac{c_0^2}{4a^2}} \tag{19}$$

where $a = 2.032$ mm for the WR-8 waveguide at $T_{\rm ref} = 295$ K. According to (3), $\lambda_{gc} = 3.408\,34$ mm at 114.800 GHz. In Table I, calculated values are presented for the center frequencies of the stopbands $f_{\rm susb}$ and $f_{\rm slsb}$ ($\theta = \pm\pi$) for $n = 7, \cdots, 11$. For the maximum LO noise attenuation, $f_{\rm susb}$ should be close to $f_{\rm rf} = 118.750$ GHz and $f_{\rm slsb}$ close to $f_{\rm im} = 110.850$ GHz. Consequently, we select $n = 9$, which yields $f_{\rm susb} = 118.585$ GHz and $f_{\rm slsb} = 111.100$ GHz. The corresponding ring length is $l_0 = 30.6751$ mm along the center line. No special computation has been carried out for determining λ_g in the vicinity of the coupler sections since tuning the gap can be used to match the effective λ_g of the ring. Need for initial tuning also arises due to uncertainties in l_0 and a_0.

[2] The frequency is an average of the two LO frequencies.

TABLE I
CALCULATED STOPBAND CENTER FREQUENCIES FOR DIFFERENT n AND $f_c = 114.800$ GHz

n	$f_{\rm susb}$ [GHz]	$f_{\rm susb} - f_{\rm rf}$ [MHz]	$f_{\rm slsb}$ [GHz]	$f_{\rm slsb} - f_{\rm im}$ [MHz]
7	119.682	932	110.060	-790
8	119.065	315	110.644	-206
9	118.585	-165	111.100	250
10	118.204	-546	111.466	616
11	117.892	-858	111.766	916

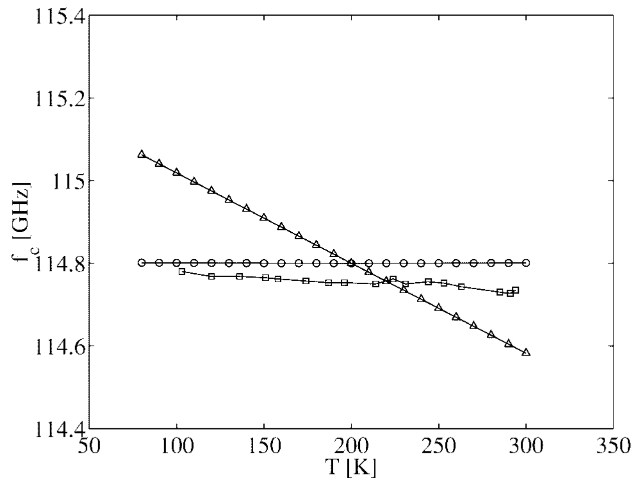

Fig. 6. Performance of Odin ring filter. Theoretical center frequency (circles), measured center frequency (rectangles), and theoretical center frequency for uncompensated ring filter (triangles).

VI. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

By substituting (14) and (15) in (4), setting $\theta = 0$, and solving for f, we actually obtain the expression for the center frequency f_c as a function of T, as shown in (20), at the bottom of this page.

For the 119-GHz ring filter, we have $l_0 = 30.6751$ mm, $\alpha_1 = 19 \cdot 10^{-6}$ K^{-1}, $\alpha_2 = 11.5 \cdot 10^{-6}$ K^{-1}, $h_0 = 12.4$ mm, $a_0 = 2.032$ mm, $T_{\rm ref} = 295$ K, and $c_0 = 2.998 \cdot 10^8$ m/s. Fig. 6 shows the theoretical $f_c(T)$ predicted by (20), and the measured $f_c(T)$. Included is also the theoretical $f_c(T)$ for an uncompensated device, made of brass, i.e., $\alpha_1 = \alpha_2 = 19 \cdot 10^{-6}$ K^{-1}. For the uncompensated curve, we have $T_{\rm ref} =$

$$f_c(T) = \sqrt{\left\{\frac{c_0 n}{l_0[1 + \alpha_1(T - T_{\rm ref})]}\right\}^2 + \frac{c_0^2}{4\{[h_0\alpha_2 - (h_0 - a_0)\alpha_1](T - T_{\rm ref}) + a_0\}^2}} \tag{20}$$

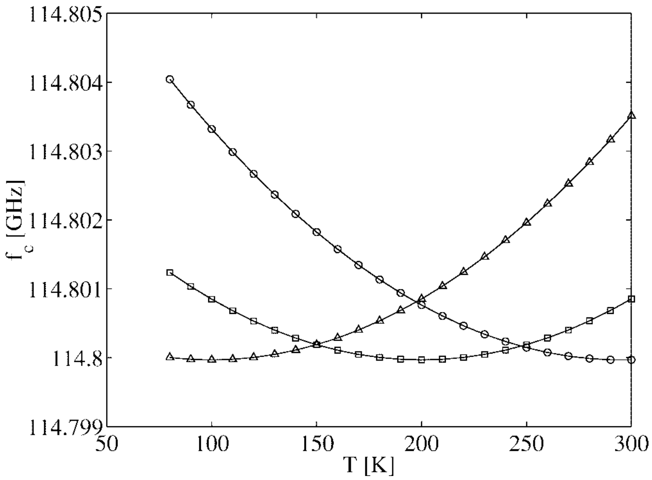

Fig. 7. Theoretical compensation action for $T_{\rm ref} = 295$ K (circles), 200 K (rectangles), and 100 K (triangles). $f_c = 114.800$ GHz at each $T_{\rm ref}$.

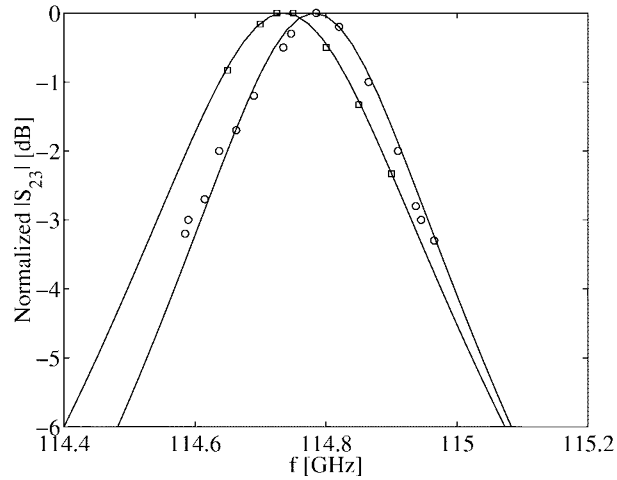

Fig. 8. Normalized measured $|S_{23}|$ at temperatures of 100 K (circles) and 295 K (rectangles). Curves are fitted to the data. The respective peaks occur at 114.780 and 114.735 GHz.

200 K, which is close to center of the temperature range and at which the center frequency is exactly correct. However, in practice, fabrication to the nominal dimensions is most easily carried out at room temperature. That is why $T_{\rm ref} = 295$ K has been selected for the compensated filter. Fig. 7 clarifies the effect of selecting $T_{\rm ref}$ on the theoretical compensation action. It can be noted that the selection is not critical since $df_c/dT \approx 0$ to a sufficient accuracy at the whole temperature range under interest for all three examples of $T_{\rm ref}$. Changing $T_{\rm ref}$ from 200 to 295 K increases the maximum detuning from about 1 to 3.5 MHz, which is still a negligible amount. The measured maximum detuning is -73 MHz at $T = 291$ K. At 100 K, which is the nominal operating temperature of the receiver front-end, a detuning of -20 MHz is observed. An uncompensated device would have a detuning of 219 MHz at 100 K and -207 MHz at 295 K. The compensation mechanism provides an improvement of 8 : 1 in the peak-to-peak variation. As can be seen in Fig. 6, the measured response is (as an average) 45 MHz below the optimum. However, at the nominal operating temperature of 100 K, f_c is close to optimum and practically minimum attenuation is achieved. It would be possible to further decrease the average detuning by slightly shortening the compensation pins.

The measured $|S_{23}|$ data at $T = 100$ K and 295 K along the corresponding curves fitted according to (2) are shown in Fig. 8. The curves are normalized. The best fit at 295 K is obtained with parameters $c = 10.8$ dB and $\alpha = 2.46$/m (21.4 dB/m). At 100 K, the best fit is achieved with $c = 10.8$ dB and $\alpha = 1.90$/m (16.5 dB/m). (It should be noted that α includes, in addition to resistive losses, leakage losses caused by the gap.) The coupling c seems to experience insignificant changes, but the increased conductivity of the gold-plated waveguide clearly reduces the attenuation of the ring resonator, which, according to (1), increases the maximum of $|S_{23}|$ up to -4.3 dB at 100 K. This is equal to a change of $+1.4$ dB compared to the measured maximum value of -5.7 dB at 295 K. (The absolute maximum of $|S_{23}|$ was not directly determined at 100 K.) The fitted curves have 3-dB bandwidths of 388 and 347 MHz at the temperatures of 295 and 100 K, respectively.

TABLE II
TRANSMISSION OF COMPENSATED AND UNCOMPENSATED RING FILTER

T [K]	$\alpha\,[\mathrm{m}^{-1}]$	$\lvert S_{23}\rvert$ [dB] Uncompensated device		$\lvert S_{23}\rvert$ [dB] Compensated device	
		114.750 GHz	114.850 GHz	114.750 GHz	114.850 GHz
100	1.90	-9.8	-7.4	-4.5 (b)	-4.9 (b)
200	2.19 (a)	-5.3	-5.3	n.a.	n.a.
295	2.46	-7.7	-9.9	-5.7	-7.0

Notes: (a) linear interpolation value between 100 K and 295 K
(b) fitted data from relative transmission measurement

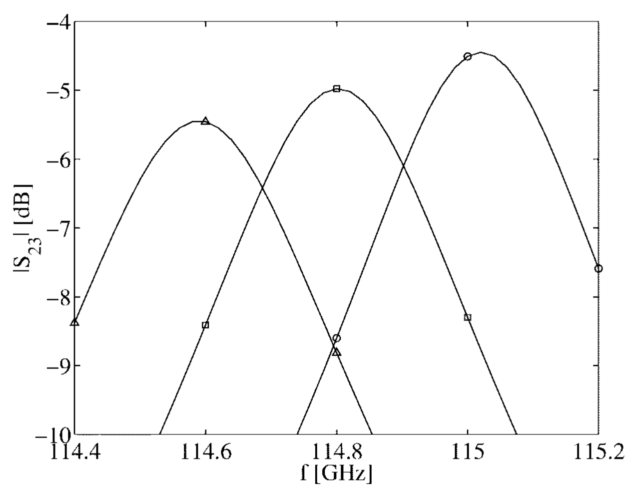

Fig. 9. Theoretical $|S_{23}|$ for uncompensated ring filter at temperatures of 100 K (circles), 200 K (rectangles), and 295 K (triangles). Dependence of α on T is taken into account according to Table II.

The total variation of $|S_{23}|$ is shown in Table II where the values indicated in Fig. 8 are added to the maximum decibel values of $|S_{23}|$ at 100 and 295 K. For comparison, theoretical performance of an optimally tuned uncompensated device (see Fig. 9), made of brass ($T_{\rm ref} = 200$ K) and calculated according to (2), is also shown. The attenuation constant at 200 K is obtained by a linear interpolation between the extreme values of 100 and 295 K.

According to Table II, the maximum change in transmission is 2.5 dB. For the uncompensated device, the change would be 4.6 dB. Considering the single LO frequency of 114.750 GHz, the respective changes are 1.2 and 4.5 dB. At 114.850 GHz, the figures are 2.1 and 4.6 dB.

The change in the conductivity of the waveguide strongly contributes to the transmission. The gold plating has a resistivity change of nearly 1 : 4 in the temperature range from 100 to 295 K, which causes a large change in the attenuation. The transmission variation due to the center frequency shift alone is 1.4 dB.

VII. Conclusion

We have presented a novel design for a cryogenic millimeter-wave ring filter, which avoids the use of external tuning aids for keeping the center frequency constant over a wide temperature range. In the application for the Odin space telescope receiver, the detuning of the center frequency has been reduced to a fraction of 1 : 8 at a temperature range from 100 to 295 K if compared to an uncompensated device made of brass. Consequently, we have been able to reduce the LO power variations due to the peak shift to 1.4 dB at any temperature and LO frequency combination. Overall power variation, including the change in the conductivity of the waveguide gold plating, is reduced to 2.5 dB for any temperature and LO frequency combination. With the novel design, we avoid the use of an external passband tuning system. This reduces the receiver complexity and increases the reliability, which together make the ring filter especially suitable for space applications.

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