A DIRECTIONAL FILTER DIPLEXER USING OPTICAL TECHNIQUES FOR MILLIMETER TO SUBMILLIMETER WAVELENGTHS*

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Abstract. An optical diplexer for injection of a local oscillator into a mixer, useful in the submillimeter and short millimeter range, is described. It has very low insertion loss for both the signal and local oscillator (L.O.) and high rejection of L.O. noise. Measured performance of a unit tested at 337 GHz indicates ∿.2 dB loss for both inputs and 20 dB noise rejection.

INTRODUCTION

The performance of mixers for the submillimeter and short millimeter range is often seriously degraded by losses involved in combining the signal and local oscillator (L.O.), particularly when L.O. power is limited. At 100 GHz, losses for the best waveguide cavity directional filter diplexers are 3-4 dB for the L.O. and ∿.5 dB for the signal.[1,2] Quasi-optical diplexers using Fabry-Perot resonators have been found to be of fairly comparable performance at 100 GHz[3] and at 186 GHz[4]. This technical note describes a different type of quasi-optical diplexer, in use with a mixer for the 300-350 GHz range, having very low loss for both the signal and L.O.

This diplexer is similar to one first described by Fedoseyev and Kulikov[5] using oversized waveguide, but differs in that it has been folded into a more convenient configuration, and uses totally free-space propagation. The actual configuration is much like a Michelson interferometer, while its action is equivalent to a directional filter.

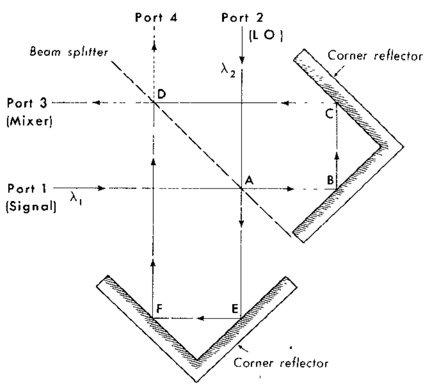

Fig. 1 Schematic diagram of diplexer showing the paths of two input rays.

Figure 1 shows schematically the operation of the diplexer. The beam splitter is assumed lossless with reflectivity amplitude r, and transmission amplitude t, with $|r|^2 + |t|^2 = 1$. A general requirement for lossless symmetric beam splitters is that r and t differ in phase by 90°, referenced to the plane of symmetry. An incoming wave from port 1 is split by the beam splitter into two beams traversing paths ABCD and AEFD which differ in length by an amount Δ. Assuming unit input amplitude, and neglecting diffraction, the net amplitude reaching port 3 (ignoring arbitrary phase factors) is

$$A_{1,3} = |t|^2 - |r|^2 e^{j2\pi\Delta/\lambda_1} \quad (1)$$

This may be made of unit magnitude if $\Delta = (N+\frac{1}{2})\lambda_1$, where N is an integer. Similarly, a wave of different wavelength and unit amplitude entering port 2 will have an amplitude at port 3 of

$$A_{2,3} = rt\,(1 + e^{j2\pi\Delta/\lambda_2}) \quad . \quad (2)$$

If $\Delta = M\lambda_2$, where M is an integer, then $A_{2,3} = 2rt$ which is also of unit magnitude if $|r|^2 = |t|^2 = .5$. If $|r| \neq |t|$, then some of the input from port 2 will leave via port 4. A graph of power transmission versus frequency is shown in Figure 2 for two beam splitter reflectivities. It should be noted that both sidebands are accepted.

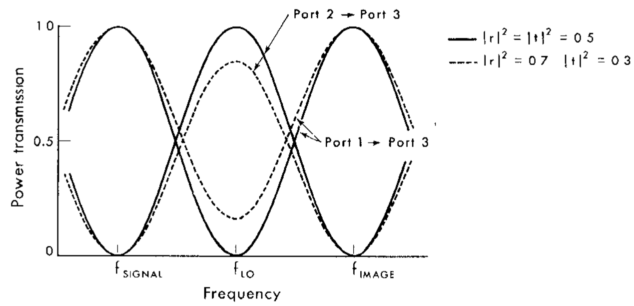

Fig. 2 Theoretical power transmission versus frequency for the two inputs, for two different beam splitter reflectivities.

Since even an unbalanced beam splitter allows unit transmission from port 1 to port 3, it is apparent that port 1 is the ideal input for the signal, with port 2 the L.O. input and the mixer on port 3. An additional benefit of this choice is that noise on the L.O. at the signal and image frequencies is rejected and exits via port 4. This rejection is theoretically better than 20 dB over a bandwidth of 12.7% of the IF center frequency.

The simultaneous conditions on the path difference stated above require that

$$\Delta = (2K+1)\,\frac{\lambda_{IF}}{2} \quad \text{and} \quad f_{signal} = \frac{(2J+1)}{(2K+1)}\,f_{IF} \quad (3)$$

where J and K are integers, (K=0 for maximum IF bandwidth), and f_{IF} and λ_{IF} are the intermediate frequency and wavelength. These two conditions are not rigorously required, of course, because there is a reasonable bandwidth to the diplexer. However, the signal frequency can never be an exact even multiple of the IF unless the signal and L.O. ports are interchanged.

While the above discussion does not consider losses in various elements, the only important signal-port loss, except for diffraction, which is considered later, is the absorption of the beam splitter. An important advantage of this type of diplexer is that this loss enters only as the absorption upon a single encounter, rather than the loss upon multiple encounters as in Fabry-Perot resonators.

DESIGN CONSIDERATIONS

The present device was designed with the only focusing optics on the inputs and output. With this constraint the smallest dimensions result for a beam waist (minimum diameter) in the optical center of the path, with the radius of curvature of the input beam wavefront (converging) equal to the total path length (input to output). This situation is similar to the optics in a confocal resonator.[6] For a Gaussian input beam of aper-

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ture distribution $A(r) = A_0 \exp(-r^2/w^2)$, this condition requires that $w = (\lambda L/\pi)^{\frac{1}{2}}$ where L is the total path. This beam will contract to a beam waist of radius $w_0 = w/\sqrt{2}$. For a more complex beam profile a conservative design is to allow clearance for a beam of radius 2w. Simple geometrical considerations require that the total path be greater than 6 beam diameters, resulting in the minimum design diameter,

$$D \equiv 4w = \frac{96}{\pi} \lambda = 30.6 \lambda \quad . \tag{4}$$

A second condition, also due to diffraction, is that the delayed and undelayed beams be capable of interfering when they are recombined. This requires that $\Delta \ll 2\pi w_0{}^2/\lambda$. The maximum value of Δ depends considerably on the aperture distributions involved. For the case of Gaussian beams, and with $|r|^2=|t|^2=.5$, the power transmission is

$$T_{Gaussian} = \frac{1}{4}\left(1 \pm \frac{1}{\sqrt{1 + \left(\frac{\lambda\Delta}{2\pi w_0{}^2}\right)^2}}\right)^2 \tag{5}$$

where the plus sign is taken for the transmission maxima and the minus sign for the minima (L.O. noise rejection). In general the maxima will be less and the minima greater for any more complex beam because of the higher modes.[6]

EXPERIMENTAL RESULTS

The actual device is used in a heterodyne receiver using a conventional waveguide mixer with a rectangular horn, and an optically pumped laser at 337 GHz as the L.O.[7] The diplexer is intended for use at an IF greater than 1.4 GHz. The clear aperture is 38 mm with w = 9.5 mm. Quasi-ellipsoidal mirrors are used on the inputs and output, with significant near-field corrections applied near the edges. These corrections are needed because the mirror is within the near field of its own focus, and is off axis. The diplexer with all optics and the mixer is shown in Figure 3.

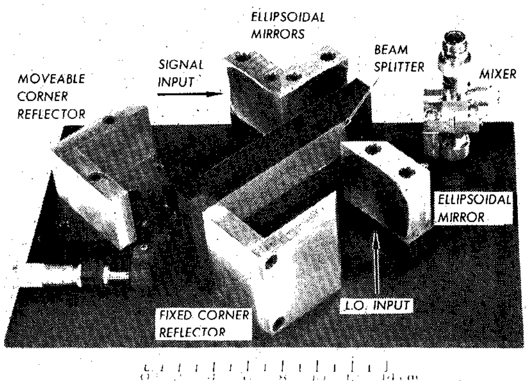

Fig. 3 Submillimeter diplexer, with ellipsoidal mirrors and mixer.

The beam splitter used is mylar, which has a refractive index of 1.69 in the one-millimeter region. The maximum two-surface reflectivity at 45° in the s polarization (electric field perpendicular to the plane of incidence) is 43%, which occurs for a thickness of .163 λ or some odd multiple of this thickness. The .13 mm thick beam splitter used has an absorption of ∿3%.

Measurements of transmission of laser power as a function of path difference are good to only about 5% because of standing-wave interactions. Power transmitted from port 2 to port 3 at zero path difference is 95%, and most of this loss is due to the beam splitter. No measurements of transmission from port 1 to port 3 have been made, but losses must be even lower between these ports. An experimental plot of transmission (2→3) versus path difference at maximum and at minimum is shown in Figure 4, compared with the theoretical Gaussian transmission given by Equation (5). The experimental points are all normalized relative to zero path transmission, and the maximum path difference of 166 mm corresponds to $\lambda\Delta/2\pi w_0{}^2 = .52$. In the experimental case the input beam is launched by an essentially uniformly illuminated aperture at the focus of the input ellipsoid, and received by the rectangular horn on the mixer at the output focus. Power transmission is measured using the mixer diode as a video detector. The transmission at maximum shows good agreement with theory, but the depth of the minima show substantial discrepancies, evidence for the expected higher modes.

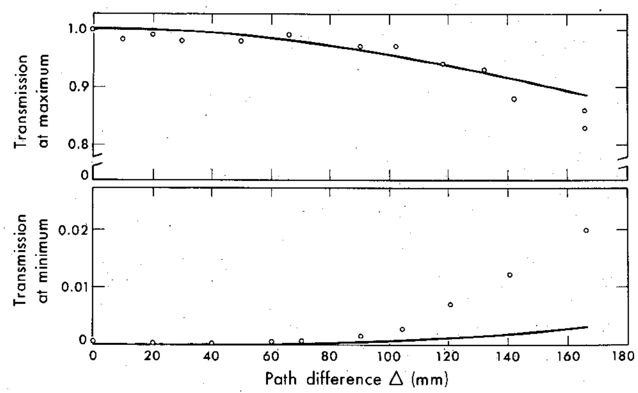

Fig. 4 Power transmission at maximum and minimum versus path difference. Points are experimental, solid curve is theoretical.

Noise rejection bandwidth can only be inferred since the laser is noiseless and non-tunable. The change in path which allows a null of better than 1% is .038 mm which implies a fractional bandwidth for 20 dB noise rejection of ∿8% of the IF. This is less than the 12.7% expected theoretically but is still adequate for most receiver applications.

No particular attempt has been made to minimize the size of this device since it is already reasonably small (20 cm x 25 cm x 7 cm). However, careful design using multiple focusing elements should allow use to wavelengths of about 3 mm with only a slightly larger size. The nature of this diplexer allows its use to much higher frequencies with very little increase in loss; in the 100 GHz region, its use would allow the operation of mixers with about half the L.O. power that is presently required, and with negligible signal loss.

REFERENCES

1. J. Davis, private communication.
2. B.D. Moore and J.R. Cogdell, "A millimeter wave directional filter cavity," IEEE Trans. Microwave Theory Tech., vol. MTT-24. pp. 843-847, Nov. 1976.
3. P.F. Goldsmith, "A quasioptical feed system for radioastronomical observations at millimeter wavelengths," to be published in Bell Syst. Tech. J., Oct. 1977.
4. J.J. Gustincic, "A quasi-optical receiver design," Digest of the 1977 IEEE-MTTS International Microwave Symposium, San Diego, Ca., pp. 99-101.
5. L.I. Fedoseyev and Yu. Yu. Kulikov, "Superheterodyne radiometers for the millimeter and submillimeter bands," Radio Eng. and Electron. Phys., vol. 16, pp. 637-641, April 1971.
6. H. Kogelnik and T. Li, "Laser beams and resonators," Appl. Opt., vol. 5, pp. 1550-1567, Oct. 1966.
7. S.F. Dyubko, V.A. Svich, and L.D. Fesenko, "Submillimeter-band gas laser pumped by a CO_2 laser," JETP Lett., vol. 16, pp. 418-419, Dec. 1972.