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Quasi-Optical Power Combining Based on Two-dimensional Meniscus Lens*

ZHAO Huai-cheng[1,2], WU Xi-dong[2,3,†], ZHANG Jin-dong[1], WU Wen[1]
(1 *Ministerial Key Laboratory of JGMT*, *Nanjing University of Science and Technology*, *Nanjing* 210094, *China*)
(2 *Department of Information and Electronic Engineering*, *Zhejiang University*, *Hangzhou* 310027, *China*)
(3 *State Key Laboratory of Millimeter Waves*, *Southeast University*, *Nanjing* 210096, *China*)

Abstract: A waveguide-based two-dimensional meniscus thin lens is proposed for mm-wave quasi-optical power combining in a closed structure. The proposed waveguide lens is operated in TE_{10} mode, and the effects of the dispersion are discussed. A matching layer is included to improve the combining efficiency. A ten-way power combiner using Rexolite material is given as a designed example at 30 GHz. Simulations show that the designed meniscus lens can achieve a combining efficiency of 92.6% at the design frequency of 30 GHz, and cover the entire Ka-band with more than 80% efficiency.

Key words: Meniscus lens; Quasi-optical; Power combining; Mm-wave
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0 Introduction

Recently, hyperbolic lens has been demonstrated for mm-wave wireless applications[1-2] and for quasi-optical power combining in a closed structure at mm-wave frequencies[3]. This paper further continued the research in Ref. [3] by using a two-dimensional meniscus thin lens inside a rectangular waveguide. Simulation results show that combining efficiencies of 80.4% ~ 94.6% can be achieved across the entire Ka-band. The proposed power combiner can be easily extended to upper mm-wave frequencies, and is well suited for broadband power combining applications.

1 Theory

Fig. 1 shows a general diagram of a two-dimensional meniscus thin lens. As shown, the focal point of the meniscus thin lens is located at point F, while D and f are the diameter and focal length of the meniscus thin lens, respectively. The meniscus thin lens has a cylindrical inner surface and an elliptic outer surface. In Cartesian coordinates, the meniscus surface can be described as

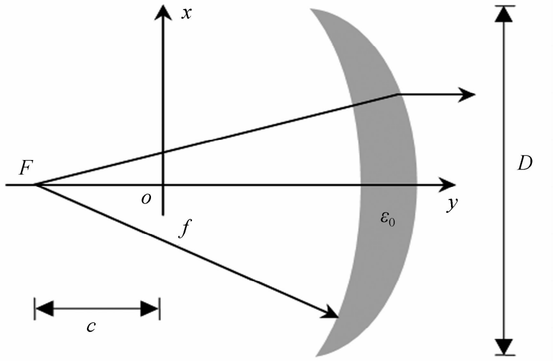

Fig. 1 Two-dimensional configuration of a meniscus lens

Inner surface: $x^2+(y+c)^2=f^2$ (1)

Outer surface: $x^2/a^2+y^2/b^2=1$ (2)

where

$$b=(n^2 f-n\sqrt{f^2-D^2/4})/(n^2-1) \quad (3)$$

$$a=\sqrt{n^2-1}\,b/n \quad (4)$$

$$c=b/n \quad (5)$$

and n is the refractive index of the thin lens material. Similarly to the hyperbolic thin lens[3], the smaller the f/D number, the thicker the meniscus lens is. In practice, too small f/D numbers should be avoided since they can result in an outer surface larger than half elliptic surface. In this case, the lens will not be well illuminated and it becomes too thick for practical applications. The limiting case is when the outer surface becomes equal to half elliptic surface, which implies

$$D=2a \quad (6)$$

Solving Eq. (6) by using Eqs. (3) and (4), the corresponding minimum f/D number can then be found as

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* Supported by the NSFC grant(60871010)

† Tel: 0571-87951789 Email: xwu@zju.edu.cn

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$$f/D \geqslant n/(2\sqrt{n^2-1}) \qquad (7)$$

2 Structure and simulations

The quasi-optical power combiner described in this paper is designed by using a two-dimensional meniscus thin lens inside a rectangular waveguide. As shown in Fig. 2, the combiner consists of side-by-side input waveguides (e. g. , ten inputs in this design), a meniscus thin lens with a matching layer, and an *E*-plane sectoral horn. To achieve maximum combining efficiency, the meniscus thin lens is placed so that its focal point *F* coincides with the imaginary apex of the *E*-plane sectoral horn (dashed line). The ten inputs are firstly coupled into plane waves inside dielectric loaded oversize waveguide. The meniscus thin lens transform the incident plane waves to cylindrical waves, which are then collected by using the *E*-plane sectoral horn as output. The thickness of the matching layer can be optimized to achieve the best matching at the design frequency.

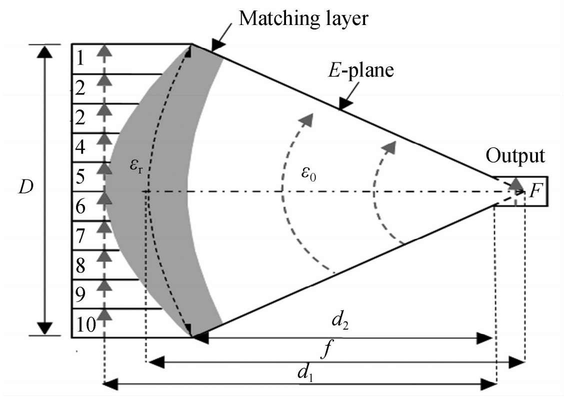

Fig. 2 Waveguide-based power combiner using meniscus thin lens

The wave number of the TE_{10} mode for a dielectric-filled waveguide can be written as

$$k_d = k_0\sqrt{\varepsilon_r-(\lambda_0/2a)^2} \qquad (8)$$

where λ_0 is wavelength in free space, k_0 is wave number in free space, ε_r is the permittivity of the filled dielectric and a is the height of the rectangular waveguide. The relative index of refraction of the meniscus lens can then be written as

$$n=\frac{k_d}{k_a}=\sqrt{\varepsilon_r-(\frac{\lambda_0}{2a})^2}\Big/\sqrt{1-(\frac{\lambda_0}{2a})^2} \qquad (9)$$

where k_a is the wave number of the TE_{10} mode for an air-filled waveguide. It should be noted that the relative index of refraction is frequency dependent due to the dispersion of the TE_{10} mode. As a result, the focal position of the meniscus lens will change with frequency, leading to a degraded combining efficiency over a frequency band. Therefore, the combiner should be carefully designed to minimize the effects of the dispersion.

In this design, a low-cost polymer material (Rexolite, $\varepsilon_r = 2.54$) was chosen due to its ease of machining and its low loss tangent. The design frequency was picked at 30GHz. Of course, the design procedures equally apply to other frequencies by simply changing λ_0 in the above equations. The corresponding minimum f/D number can be calculated as 0. 576 from Eq. (7).

In this paper, meniscus thin lenses with f/D number from 1. 6 to 2. 4 have been investigated. The diameter of the lens is fixed to be $D = 10b = 35.56$ mm for all cases, where b is the width of the input waveguide ($b = 3.556$ mm for WR-28). Once the focal length f, diameter D and index of refraction n are known, the surface of the meniscus lens can then be determined by using Eqs. (1)～(5).

Fig. 3 shows the simulated combining efficiency for f/D number of 1. 6 by using CST-MWS. The combining efficiency is defined as the ratio of the output power to the total input power when all the ten input waveguide ports are equally excited.

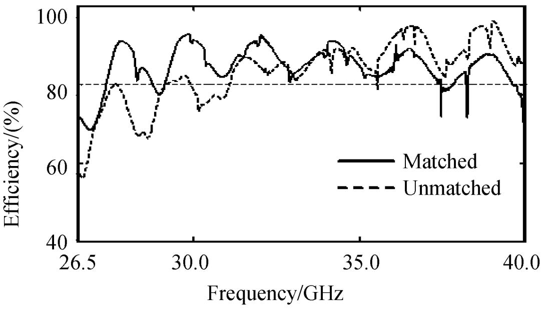

Fig. 3 Simulated combining efficiency for f/D number of 1. 6

$$\eta = P_{out}/\sum P_i = P_{out}/(10P_1)\times 100\% \qquad (10)$$

As shown, the combiner can only achieve an efficiency of 78. 5% at the design frequency of 30 GHz if without matching layer. However, the efficiency can be improved to 91. 2% at 30 GHz by introducing an optimized 1. 0 mm matching layer. The optimized combiner exhibits a bandwidth of 8. 2 GHz with efficiency larger than 80%. The efficiency oscillations observed in both cases are believed to be caused by the dispersion of the designed meniscus lens and by the multiple reflections inside the meniscus lens and the *E*-plane sectoral horn. Therefore, a better design seems to come out with a thinner lens and a larger cavity region, which implies a larger f/D number meniscus lens.

In this enlightenment, a power combiner with larger f/D number is investigated. Fig. 4 gives the simulated combining efficiency for f/D number of 2.4. As shown, the broadband efficiencies are greatly improved. The combining efficiency at the design frequency 30 GHz is found to be 92.6%, and the combiner exhibits efficiencies of 80.4%~94.6% across the entire Ka-band. The proposed power combiner can be easily extended to upper mm-wave frequencies, and is well suited for broadband power combining applications.

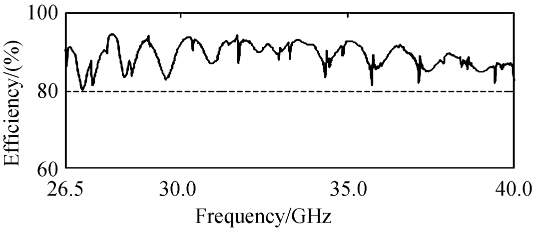

Fig. 4 Simulated combining efficiency for f/D number of 2.4

3 Conclusion

This paper demonstrated a broadband quasi-optical power combiner using a two-dimensional meniscus thin lens inside a rectangular waveguide. One of the advantages of this approach is that the proposed combiner can be integrated inside a closed structure, thus eliminating any possible interference. Effects of f/D number of the meniscus lens were investigated. According to the CST simulations, the operation bandwidth of the proposed combiner increases with the f/D number of the meniscus lens. A ten-way power combiner using Rexolite material was then designed at 30 GHz. Simulations show that combining efficiency of 80.4% ~ 94.6% can be achieved across the entire Ka-band with the f/D number of 2.4. The proposed power combiner is attractive for high power mm-wave applications because of its closed structure and high efficiency.

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基于二维 Meniscus 透镜的准光功率合成器

赵怀成[1,2],吴锡东[2,3],张金栋[1],吴文[1]
(1 南京理工大学 近程高速目标探测技术国防重点学科实验室,南京 210094)
(2 浙江大学 电子信息工程系,杭州 310027)
(3 东南大学 毫米波国家重点实验室,南京 210096)

摘　要:为了实现大功率容量和高效率的空间功率合成,将基于波导腔体的二维 Meniscus 透镜用于毫米波功率合成器的设计.对透镜中传输的主模(TE_{10}波)的散射效应进行了分析,并且设计了匹配层减小透镜结构带来的反射.在 30 GHz 频率上利用 Rexolite 介质的 Meniscus 透镜设计出了 10 路功率合成器,对不同结构的功率合成器和不同参数的透镜进行了研究,得到了最终的优化结果.CST-MMW 的仿真结果表明该功率合成器在 30 GHz 合成效率可以达到 92.6%,并且其 80%以上效率工作带宽可以覆盖整个 Ka 波段.

关键词:Meniscus 透镜;准光功率合成;毫米波

ZHAO Huai-cheng received the M. S. degree in electric engineering from Nanjing University of Science and Technology. Now he is pursuing the Ph. D. degree in electromagnetic field theory, and his research interests focus on microwave antenna and lens power combining.

WU Wen was born in 1968 and received the Ph. D. degree from Southeast University. Now he works as a professor at Nanjing University of Science and Technology, and also serves as a vice Director of the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology.