Application of gaussian beam based techniques to the quasi-optical systems of radiofrequency radiometers

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Application of Gaussian-Beam based Techniques to the Quasi-Optical Systems of Radiofrequency Radiometers

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***Abstract*—The electromagnetic performances of the quasi-optical systems may be critical in the design of a mm-wave radiometer. We propose to compute these performances by means of gaussian-beam based techniques. Numerical and experimental tests reveal a good trade-off between the accuracy and the computational effort.**

I. Introduction

In mm-wave radiometry, quasi-optical systems are used to guide, filter, split or mix the input signals. Such systems are generally constituted by the combination of different elements, e.g. mirrors, lenses, dichroic filters, or horn antennas. The number and the size of these elements render their modeling difficultly amenable by classical methods in acceptable computation times. For such systems, even physical optics may become computationally too costly.

Gaussian beams constitute a possible alternative. Historically, they have firstly been applied assuming that the system has an axial symmetry [1]. The incident field is approximated by a single gaussian beam. When passing through the elements of the system, this beam is transformed into reflected/transmitted beams which characteristics are determined by means of the ABCD laws. Since then, an important number of gaussian-beam based techniques have been developed in the context of quasi-optical systems [2], but also to treat other problems as radomes [3], or indoor propagation [4]. In most cases, modeling approaches based on gaussian beams are constituted by two key components: the expansion and the tracking. Expansion techniques allow for the representation of fields as discrete sums of elementary beams. Tracking techniques deal with the interaction/propagation of elementary beams through the elements of the system, e.g. the interaction of beams with dielectric and/or metallic interfaces.

In this article, we consider quasi-optical systems including horn antennas, metallic reflectors and/or dielectric lenses. We choose an appropriate expansion to describe the radiation of horn antennas from a discrete set of gaussian beams. We employ a gaussian beam shooting to deal with the tracking of the beams in the system.

Section 2 presents the expansion principles and the gaussian beam shooting algorithm. In Section 3, numerical tests are performed in order to evaluate the capabilities (accuracy/computation time) of this approach. Finally in Section 4, we present an experimental validation.

II. Method

A. Expansion

A large family of gaussian beam expansions already exists in asymptotics [7]–[9]. Our choice is based on two criteria. Firstly, we want to be free from the paraxial approximation in order to model correctly side lobes diverging with an angle greater than 20 degrees with respect to the horn axis. Secondly, we want to use as few beams as possible to reduce the computation time. Due to these criteria, we employ the pragmatic expansion developed in [3], with which a field known on a moderately curved surface is expressed as a set of equally spaced gaussian beams.

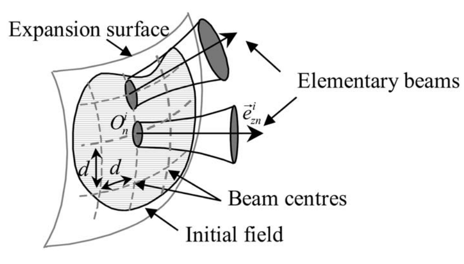


Fig. 1. Expansion principle

Note that to reduce the number of beams, the expansion characteristics are chosen from the physical properties of the configuration. Numerical experiments have demonstrated the efficiency of this approach. However, limitations exist that concern the incidence of the initial field, and the curvature of the surface, both of which must remain moderate. For the application to horn antennas, we consider a spherical expansion surface for which these limitations are not reached.

B. Gaussian beam shooting

Once the radiation of the horn antenna is described by a discrete sum of gaussian beams, the evolution of each elementary beam must be computed when passing through the quasi-optical system. In [5] Deschamps has demonstrated that the fields reflected and/or transmitted at a dielectric/metallic interface illuminated by an incident gaussian beam can be approximated by gaussian beams. Thus, we track each elementary beam of the expansion as follows. When the beam propagation axis encounters an interface, it is transformed into reflected and/or transmitted gaussian beams, which are tracked in turn. The tracking stops either when the beam power becomes neglectable, or when the beam leaves the system.

III. Implementation and validations

A. Implementation

The method presented in the previous section is implemented in a Scilab program, named QOSGB (quasi-optical systems via Gaussian beams), which is able to model systems made of mirrors, lenses, and horn antennas. This program is splitted in two parts. In the first part, the expansion and tracking are performed, so as to represent the field in any part of the system as a combination of Gaussian beams. In the second part, beams are sumed in order to obtain numerical values for the fields. Note that the paraxial formulation of gaussian beams is used for observation points inside/near the system, whereas the far-field formulation is employed for far-field patterns [3].

B. Numerical tests of the expansion

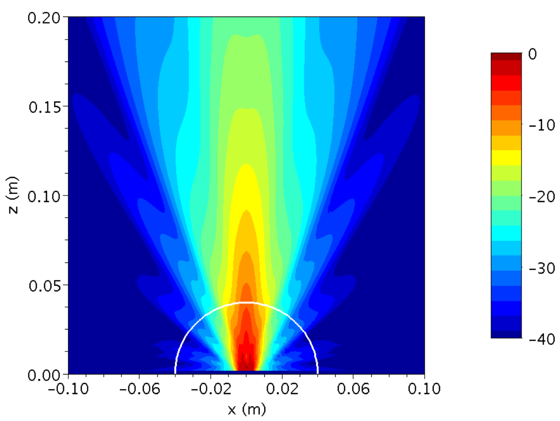


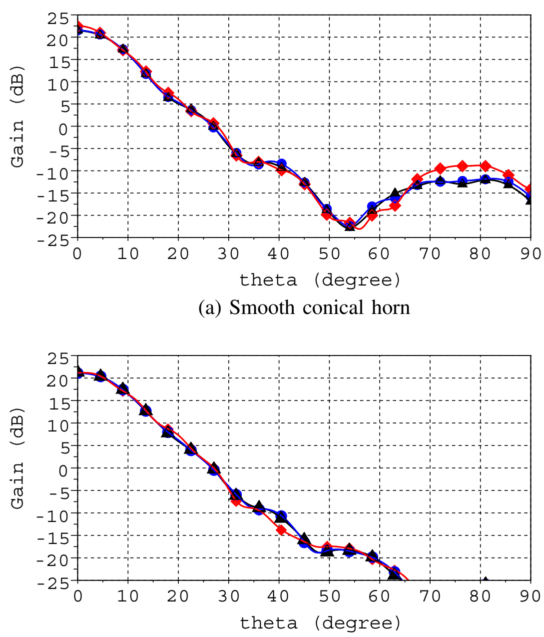
Fig. 2. Electric field obtained from the expansion (dB), the expansion surface is plotted in white

One of the goal of this article is to carefully justify the capabilities of the method we propose to model quasi-optical systems in comparison to other techniques. Firstly, we analyze the efficiency of the expansion. We consider a conical horn antenna of length 17.8mm and of diameter 10mm at a frequency of 150GHz. The horn antenna is approximated by its equivalent aperture [10]. The expansion surface is a sphere centered at the aperture center and of radius 40mm. We start our analysis with a distance between elementary beams of $d = 1.5\lambda$. According to [3], the beams are symmetric and we choose their waist size equal to d.

The expansion yields 1022 gaussian beams in 13.78s. In Fig 2, we observe the electric field obtained from the sum of the elementary beams. The general behaviour represents accurately the horn radiation. We have verified that the difference between this result and a reference solution is below -40dB except very near the aperture.

In Fig. 3(a), we compare the far-field pattern in the E-plane obtained for different values of d. For larger values of d, we observe that the accuracy is slightly deteriorated. Concerning the computational cost, when d is set to 2λ and 3λ, the number of beams becomes 594 and 291, which corresponds to computation times of 3.73s and 1.62s, respectively. Small values of d lead to use more expansion beams, and consequently to a better accuracy and a longer computation time. As illustrated in Fig. 3(b), the same remarks hold when the horn is corrugated.

Finally, the expansion treats accurately the radiation of horn antennas with a few hundred elementary beams, so as to yield an inexpensive computational cost.



(a) Smooth conical horn

(b) Corrugated conical horn

Fig. 3. Gain pattern (dB) of the horn antenna in the E-plane for $d = 1.5\lambda$ (black with ▲ markers), $d = 2\lambda$ (blue with ● markers), and $d = 3\lambda$ (red with ◆ markers)

C. Numerical tests on a complete quasi-optical system

We consider a complete quasi-optical system working at 150GHz with three elements: the preceding corrugated conical horn, a dielectric lens, and a mirror. This configuration is displayed in Fig. 4. The lens has a relative permittivity of 2.6 and a thickness of 6mm. Its two interfaces are spheric with radius 37mm. Both are covered by an anti-reflective coating of thickness 0.394mm and relative permittivity 1.61. The mirror is a parabolic reflector of focal 100mm.

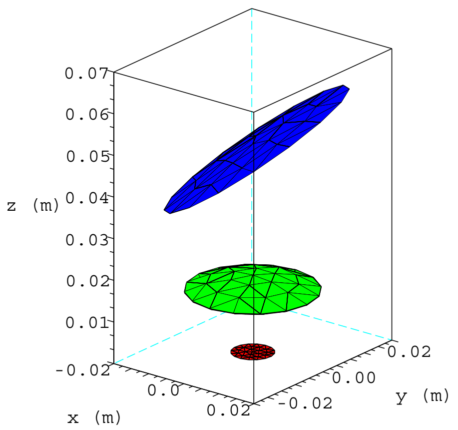
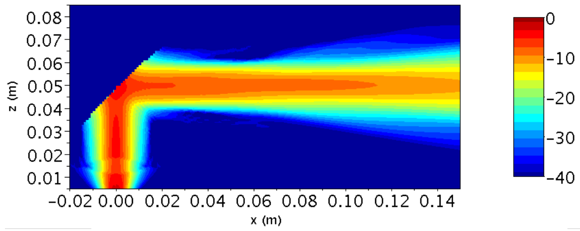
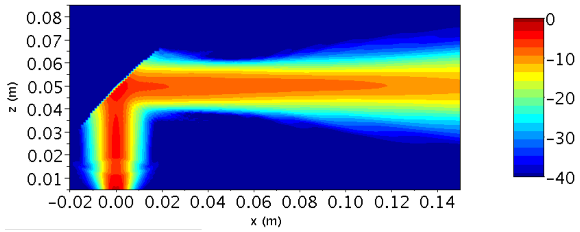


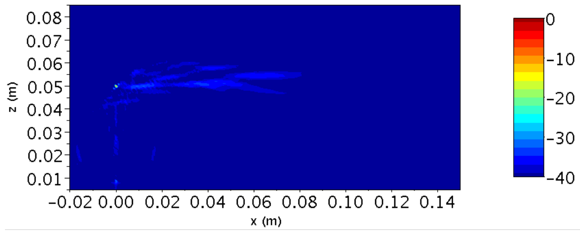
Fig. 4. Configuration of the quasi-optical system



(a) QOSGB



(b) Feko



(c) Difference

Fig. 5. Total electric field in the quasi-optical system (dB)

In Fig. 5(a), we display the total electric field obtained by means of QOSGB in the plane $y = 0$. In Fig. 5(b), we depict the total electric field obtained by Feko in the same configuration. This result is considered as a reference solution because Feko provides a numerical solution free from any physical approximation. We note a very good agreement between QOSGB and Feko. This is confirmed by Fig. 5(c), in which we observe the difference between both results that remains everywhere below -30dB. Besides, the total fields are plotted at $y = 0$ and $x = 40$mm in Fig. 6. Even after the interactions with the lens and the reflector, QOSGB fits with FEKO. These confrontations demonstrate the abilities of QOSGB to predict accurately the field inside and near the system.

We now analyze the far-field pattern of this system. In Fig. 7 and Fig. 8, we display the gain with respect to the observation angle in the E- and H-planes. The results obtained with Feko and QOSGB are very similar. Indeed, the level of the cross-polarization, sidelobes, and maximal gains are very close. For example, the maximal gain values are of 30.49dB and 30.19dB with Feko and QOSGB, respectively. Furthermore, both methods predict a boresight error of 0.3^o in the E-plane.

On a PC running at 2.4GHz, the first part of QOSGB has been performed in 13.1s. This time is relatively short, it comprises the expansion and the gaussian beam shooting. For the result of Fig. 5, the second part of QOSGB requires

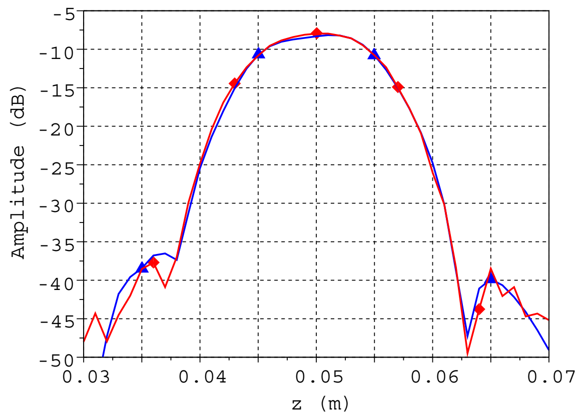


Fig. 6. Total electric field at $y = 0$ and $x = 40$mm (dB): Feko (red with ♦ markers), QOSGB (blue with ▲ markers)

12.65s. It corresponds to the computation of the field at 100×100 observation points from all the beams generated in the expansion and shooting. To obtain the result at the same observation points, the computation time of Feko using the parralelized multilevel fast multipole method of moments (MLFMM) is of order 46.18 hours.

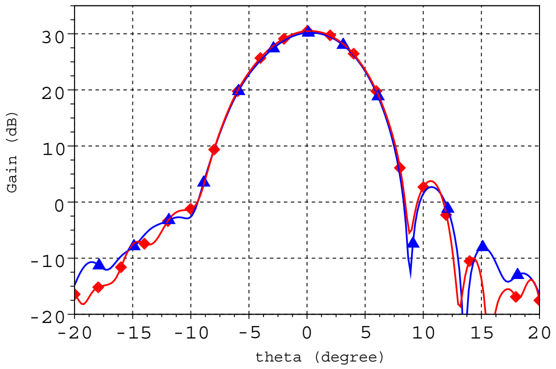


Fig. 7. Gain pattern in the E-plane (dB): Feko (red with ♦ markers), QOSGB (blue with ▲ markers), co-polarization (solid line), cross-polarization (dashed line)

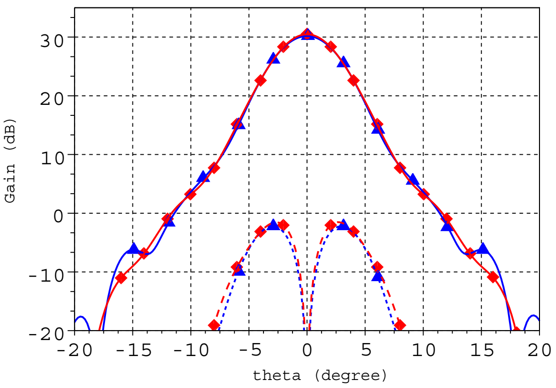


Fig. 8. Gain pattern in the H-plane (dB). Feko (red with ♦ markers), QOSGB (blue with ▲ markers), co-polarization (solid line), cross-polarization (dashed line)

Thus, in this configuration, QOSGB maintains the accuracy of the method of moments with a greatly reduced computation time. Note also that if we include any fourth element in the system, the computation was not amenable with FEKO on this PC.

IV. Experimental validation

We now consider the experimental setup of Fig. 9 working at 10GHz. In this system, we keep the horn and the lens of the previous sections, except for the size, which is ten times larger. The distance between the horn aperture and the lens center is of 525mm. Note also that the horn is not corrugated, and vertically polarized. In order to measure the vertical electric field, we place a vertical dipole that can move in a volume beyond the lens.

In Fig. 10, we represent the measured electric field in a vertical plane. In this figure, the reference frame center $x = y = 0$ is placed at the horn aperture. We note the presence of perturbations on both sides of the system.

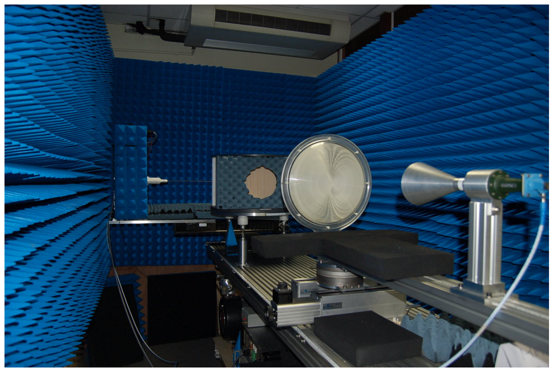


Fig. 9. Picture of the experimental setup

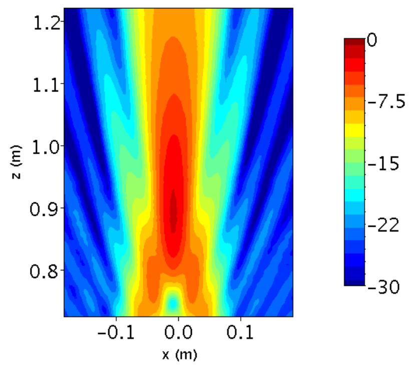


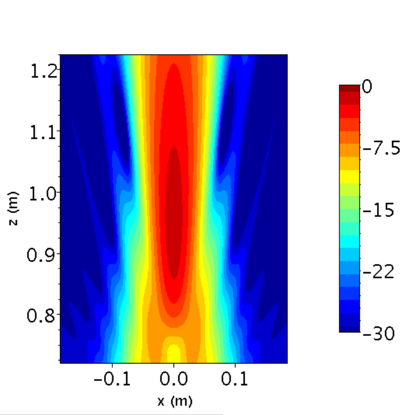
Fig. 10. Vertical component of the electric field (dB) obtained from measurements

In Fig. 11(a) and (b), we compute this configuration with Feko and QOSGB. We observe that the general behaviour of the field is well reproduced. More particularly, the field spatial spread and the minimum value near $x = 0, z = 0.75$m are similar. Nevertheless, there are differences in the focal zone position, and in the field outside the central region, i.e. for $|x| > 0.1$m. These differences may be explained by side effects on the lens edge. Indeed, the lens used in the measurements is bordered by a plexyglass support, which has not been included in the simulation. Besides, we have chosen to not model edge effects in QOSGB because this program is designed for mm-waves quasi-optical systems, in which side effects are generally neglectable. Nevertheless, note that approaches exist to deal with side effects with gaussian beams [11], [12].

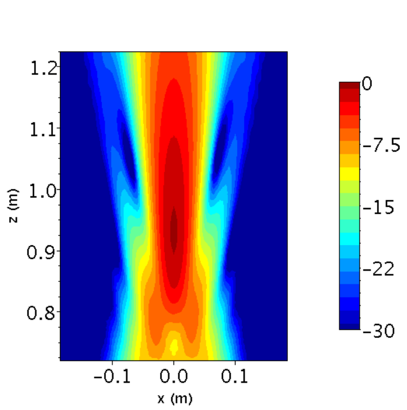
In order to confirm the importance of the edge diffraction by the lens in this configuration, we display with QOSGB the incident field that arrives at the lens from the horn antenna in Fig 12. On the edge, the incident field is only 10dB lower than its maximal value on the lens, which validates our hypothesis.

V. Conclusion

In this article, the aim was to propose an asymptotic modeling technique based on gaussian beams, in the context



(a) Feko



(b) QOSGB

Fig. 11. Vertical component of the electric field (dB)

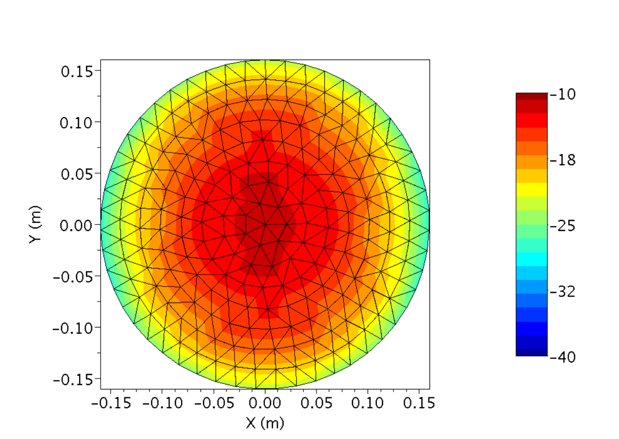


Fig. 12. Tangential incident electric field at the surface of the lens (dB)

of quasi-optical systems. To this end, we have chosen an expansion method to describe the radiation of horn antennas with a few hundred gaussian beams. We have numerically verified that this expansion achieves a good trade-off between computation time and accuracy. After the expansion, the beams are tracked in the system by means of a shooting algorithm. In a comprehensive test case, we have shown that this method maintains the accuracy of the method of moments with a greatly reduced computation time. Finally, the method has been confronted to measurements realized with a setup containing an horn antenna and a lens. The comparisons have been satisfying, except for the diffraction by the lens edge that is not accounted in our approach.

For future works, other elements as dichroic surfaces shall be incorporated in QOSGB in order to be able to model more general types of quasi-optical systems. This would require research works to investigate the interaction of gaussian beams with periodic surfaces.

VI. Acknowledgments

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