Advanced designs for non-imaging submillimeter-wave Winston cone concentrators

A.O. Nelson[a,b], E.N. Grossman[a]
[a]NIST Boulder Laboratories, Boulder, CO 80305 USA;
[b]University of Colorado at Boulder, Boulder, CO 80309 USA

ABSTRACT

We describe the design and simulation of several non-imaging concentrators designed to couple submillimeter wavelength radiation from free space into highly overmoded, rectangular, WR-10 waveguide. Previous designs are altered to improve the uniformity of efficiency rather than the efficiency itself. The concentrators are intended for use as adapters between instruments using overmoded WR-10 waveguide as input or output and sources propagating through free space. Previous simulation and measurement have shown that the angular response is primarily determined by the Winston cone and is well predicted by geometric optics theory while the efficiencies are primarily determined by the transition section. Additionally, previous work has shown insensitivity to polarization, orientation and beam size. Several separate concentrator designs are studied, all of which use a Winston cone (also known as a compound parabolic concentrator) with an input diameter ranging from 4 mm to 16 mm, and "throat" diameters of less than 0.5 mm to 4 mm as the initial interface. The use of various length adiabatic circular-to-rectangular transition sections is investigated, along with the effect of an additional, 25 mm waveguide section designed to model the internal waveguide of the power meter. Adapters without a transition section and a rectangular Winston cone throat aperture and double cone configurations are also studied. Adapters are analyzed in simulation for consistent efficiency across the opening aperture.

Keywords: compound parabolic concentrator (CPC), concentrator, overmoded waveguide, power meter, submillimeter-wave, terahertz (THz), Winston cone, PM4, Thomas Keating power meter, metrology.

1. INTRODUCTION

Highly overmoded waveguides (often described as "light-pipes") have been widely used in the submillimeter-wave band for decades, largely because of their versatility, particularly in terms of frequency coverage, and their ease of fabrication. As technology for this frequency range matures, instrumentation that employs overmoded waveguide at its input or output must be made compatible with systems that use other transmission media. In this work, we are particularly concerned with a very widely used absolute power meter, the PM4 [1][1], which uses standard WR-10 rectangular waveguide (2.54 x 1.27 mm, width x height) at operating frequencies up to > 1 THz, where it is very highly overmoded [2]. A commonly faced problem is using this instrument to measure the power of a THz beam in free space, either in order to compare with measurements on a separate, free-space coupled, absolute power meter [3][1] or to eliminate the need for such a power meter, which is costly and not necessarily consistent in its readings with the PM4. This problem is one of non-imaging concentration, as discussed in the comprehensive text of Welford and Winston [4]. At visible and near infrared (near-IR) wavelengths, the most important application for non-imaging concentrators is increasing the power density available from solar radiation. At far-infrared (far-IR) and submm wavelengths, the Winston cone, or Compound Parabolic Concentrator (CPC), has been widely used since the mid-1970s [5] in combination with small, non-resonant, detector cavities to improve detector efficiency in astronomical instruments.

The purpose of the present investigation is to explore an approach based on Winston cones for coupling signals in free space to the PM4 or to other existing instruments that employ highly overmoded rectangular waveguide for their input. These devices may be considered as "adapters" between two widely used transmission media: free space and overmoded waveguide. Current submm instrumentation [6] is somewhat bifurcated, as half the field is comprised of free-space-coupled devices, and half of waveguide-coupled devices. There is little capability for comparing and ensuring consistency between the two types of measurement. The ideal concentrator would couple all power, of any polarization,

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within a given radius in physical space and angular space, with constant efficiency (ideally 100%) into a collection of propagating modes in the output waveguide. We emphasize that the actual value of the efficiency is less important than its constancy over a well-defined range of throughput space (position and angle) and a monotonic and sharp transition to zero outside that range. This is the primary difficulty with using (single-mode) horn antennas, whether standard-gain pyramidal horns, conical horns or other types, as concentrators. Such antennas display large variations (nulls and sidelobes) in their far-field angular patterns. As discussed in [4, Sec. 4.5] and [7], cones and similar reflective geometries are considerably less ideal than Winston cones in terms of the sharpness of their transition between accepted and rejected regions of throughput space.

In a previous paper [7], we introduced the Winston cone adapter and presented simulations and experimental measurements showing good uniformity of response over angular space (and polarization), in agreement with the classic geometric optics analysis of [4]. The focus of this paper is on improving the prototype designs presented in [7] to increase the spatial uniformity of response across the entrance aperture of the Winston cone. In addition, a 25 mm section of overmoded waveguide that is internal to the PM4 is now included in the simulations and in the interpretation of measured efficiencies.

The usage of the term "overmoded" can be confusing. In waveguide contexts, it denotes operation at a high enough frequency that more than one mode is above cutoff. In free space contexts, it denotes operation at a high enough frequency that the beam throughput $A\Omega$ (where A denotes its area and Ω its angular subtense) exceeds $A\Omega > \lambda^2$, where λ is the free space wavelength. A synonym for overmoded is then non-diffraction-limited.

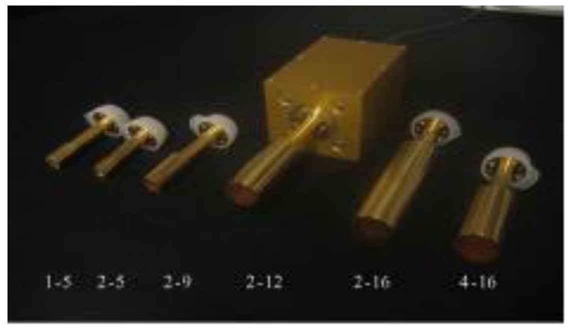

Figure 2: Photograph of the six prototypes, along with a commercial WR-10

2. PREVIOUS WORK

In our last publication [7], all investigated geometries consisted of two sections: a Winston cone with a circular input aperture and circular "throat" aperture, and a 25mm adiabatic waveguide transition from the circular throat to the rectangular WR-10 output, as shown in Fig. 1. The six prototypes shown in Fig. 2 were designed and fabricated with the

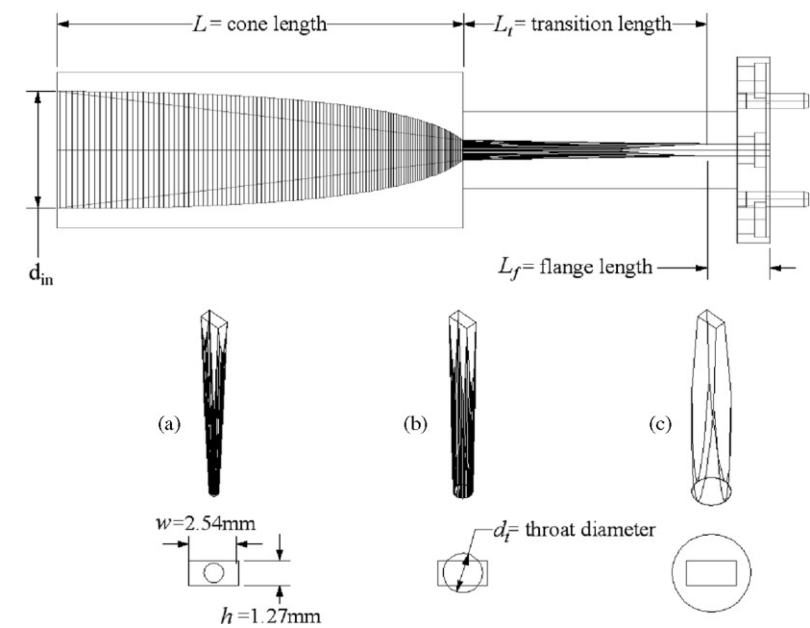

Figure 1: Geometry of the concentrator prototypes. (Top) side view of prototype, (middle) perspective views of the three cases of adiabatic transition, (bottom) end views of the three transitions.

Winston cone and transition sections fully integrated to cover a range of input and throat diameters, denoted in this work by X-Y, where X is the throat diameter in mm and Y is the input diameter in mm. These were simulated in geometric optics and then tested, in both linear polarizations for both angular patterns (orthogonal 1D cuts through the principal planes) and efficiency. The latter was obtained by direct comparison of readings from two absolute power meters, both optimized for submm wavelengths, with the Winston cone aligned with the beam center. The first power meter was free-space coupled and the second was coupled to overmoded WR-10 waveguide, to which the Winston cone adapter was attached. All measurements were performed using an optically pumped, far-IR waveguide laser operating on the 760 GHz line of formic acid. At this frequency, there are 59 TE modes and 52 TM modes above cutoff in WR-10 waveguide.

The Winston cone section was designed according to the standard relations based on the "edge-ray principle" [4, Sec. 4.2]. These provide the acceptance angle and overall length of the Winston cone according to:

$$\sin\theta = \frac{d_{out}}{d_{in}} \quad (1)$$

$$L = \left(\frac{d_{out}+d_{in}}{2}\right)\cot\theta \quad (2)$$

where L represents the cone length, θ the acceptance angle, and d_{out} and d_{in} the throat and input diameters of the cone, respectively. The concentration ratio is $CR = (d_{in}/d_{out})^2$. In accordance with the invariance of optical throughput in lossless systems [8, Sect. 2.12], a fundamental principle of radiometry, the Winston cone's input and throat apertures are related by: $A_{input}\Omega_{input}=2\pi A_{throat}$.

In both simulation and experimental measurement, it is apparent that the angular response is primarily determined by the Winston cone and is well predicted by geometric optics theory and that the efficiencies are primarily determined by the transition section. As discussed in [1, Sec 4.3], the angular response of a Winston cone in two dimensions is unity out to the acceptance angle and zero thereafter, while in three dimensions, the transition has a small but finite angular width. In experimental analysis of the prototype geometries, reproduced in Fig. 3, it is immediately evident that all the angular response curves are notably "flat-topped," especially in comparison with the beam patterns of typical single-mode horns, which typically display sidelobes and have patterns that can be approximated as quadratic near broadside. Additionally, the shape and width of the response curves do not depend on the incident polarization or on the plane of rotation, parallel or normal to the long wall of the waveguide. While the Winston cone section dominates the angular response of each geometry, the transition section appears to be the dominant determinant of the efficiency, through reflection loss at its walls. The assumed reflectance (94%) used in corresponding simulations was essentially a free parameter chosen to best match the results shown in Fig. 3.

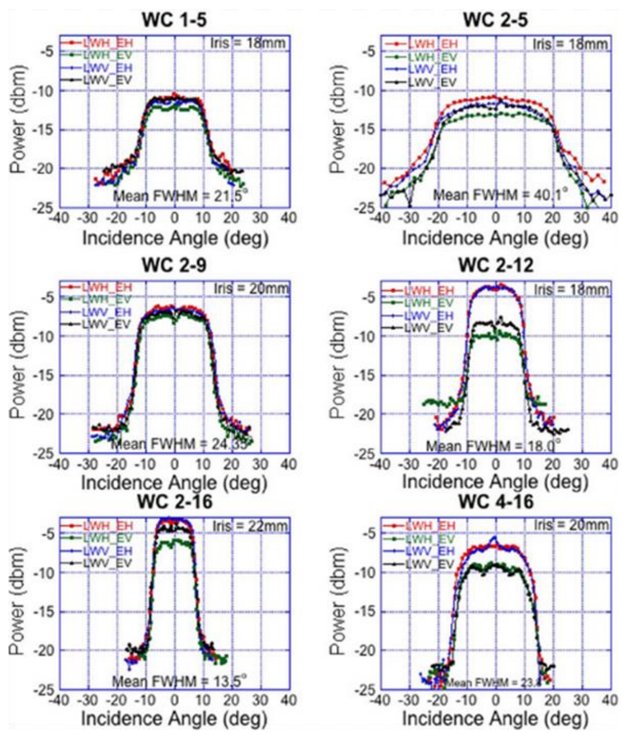

Figure 3: Experimental angular response for the six prototypes.

3. SPATIAL DEPENDENCE

The remainder of this paper presents recent work to improve upon the above geometries in terms of both efficiency and spatial uniformity. Of the six prototypes explored in [7], the area of the circular throat was approximately matched to the area of the WR-10 output for four cones (those with a throat diameter of 2mm), significantly less than the area of the WR-10 for the 1-5 cone, and significantly greater than the area of the WR-10 for the 4-16 cone. For this reason the 4-16 cone violated the throughput conservation principle, while the other five cones did not. Current work focuses on modifications to the 1-5 Winston Cone geometry designed for the previous paper because its throat area is less than the area of the WR-10 output and because its measured and simulated efficiencies matched better than the other prototypes. Additionally, as shown in Fig. 3, the 1-5 Winston cone has a very flat-topped efficiency pattern, which is close to the ideal pattern described in Section 1 of this paper. We introduce the inclusion of the internal 25mm waveguide section within the PM4 to simulations, as well as a new focus on the spatial dependence of efficiency over the entrance aperture and several new geometric designs depicted in Fig. 4.

The angular response and spatial dependence of these geometries was analyzed using a commercial, non-sequential optics simulator [9][2]. This simulator includes the Winston cones as a built-in, optical component geometry, while all other geometry was entered manually. No polarization dependence is included in the simulations, which are performed using only geometric optics and metallic reflection. This geometric optics approach ignores any lower-frequency limit, below which physical optics become significant. The wavelength dependence of the current geometries is discussed separately at the end of this publication, but a rigorous analysis is beyond the scope of this paper.

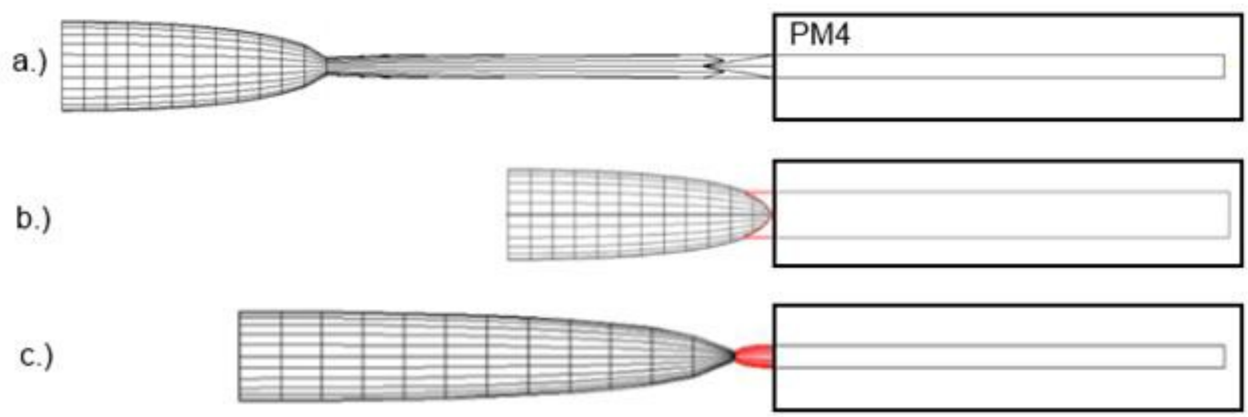

Figure 4: Concentrator geometry: (a.) shows original 1-5 Winston cone geometry used in previous publication with a 25mm transition section and 25mm of internal waveguide within the power meter. (b.) shows a 1-5 Winston cone with the "no-transition" geometry explored in this paper. (c.) shows a 0.5-5 Winston cone with another, backwards Winston cone as a transition to the internal waveguide.

3.1 Addition of internal 25mm PM4 waveguide

Previous simulation of prototype geometry did not include the internal waveguide of the power meter used in experimental measurement [10]. This additional 25mm waveguide section reduces both the average simulated efficiency of the concentrator and the uniformity of efficiency over the entrance aperture of the Winston cone, as rays entering the waveguide at steep angles accumulate significantly more reflections than rays entering at shallower angles. This contrast is shown in Figures 5 and 6, which display the spatial dependence of the original 1-5 Winston cone and 25mm transition with and without the additional 25mm internal waveguide. The additional 25mm internal waveguide section is included in all other simulations presented below. These simulations also feature a higher reflectance value than used in previous work (96.5% as opposed to 94%). Again, the reflection value chosen as a free parameter to best match experimentally measured efficiencies.

The following figures represent cross-sectional views of efficiency in 4D parameter space (two spatial dimensions spanning the plane of the entrance aperture and two angular dimensions specifying the angle of incoming collimated rays.) The angles θ_x and θ_y are measured from the normal to the plane of the entrance aperture, and range from 0 degrees to 90% of the nominal acceptance angle for each Winston cone. The waveguide is oriented with its long axis vertical (in the y-direction.) Large spots of high efficiency near the center of each plot represent rays that travel straight through the geometry without intersecting any features.

[2]The use of this commercial product does not constitute an endorsement by NIST. Other products may work equally well for this application.

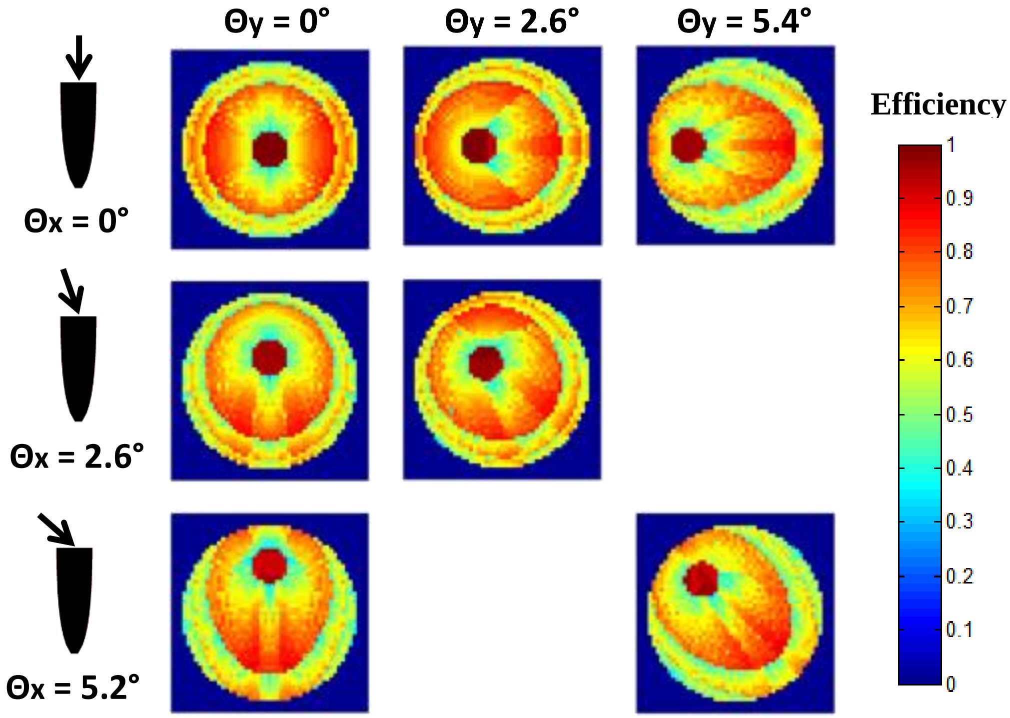

Figure 5: Spatial dependence of efficiency for the 1-5 prototype geometry used in previous work. This simulation does not contain the internal 25mm waveguide section.

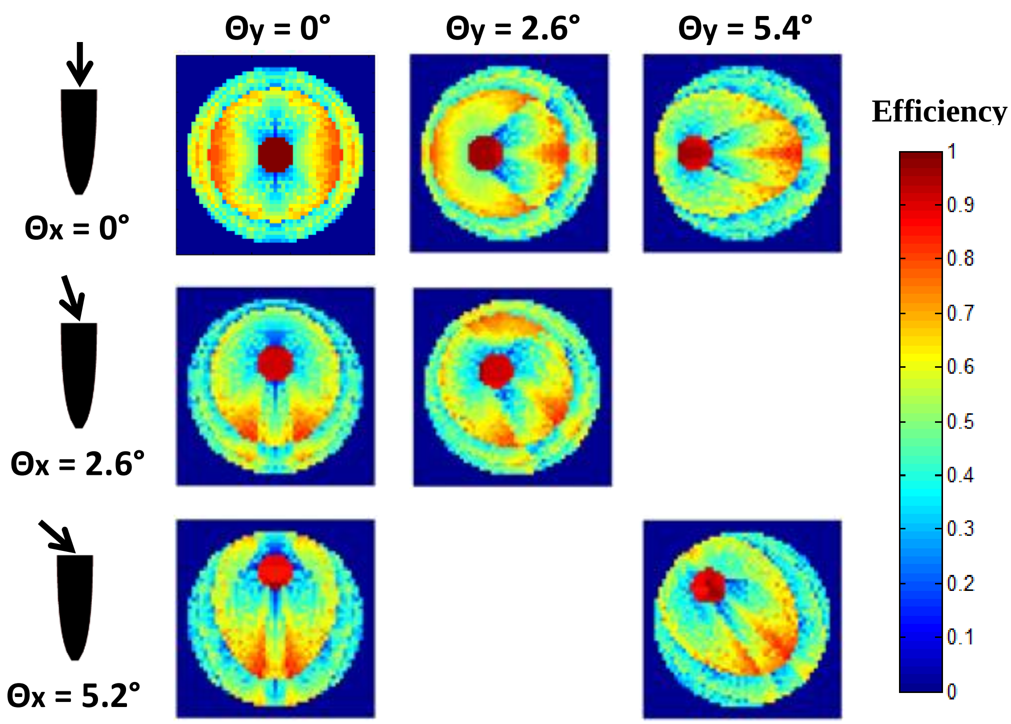

Figure 6: Spatial dependence of efficiency for the 1-5 prototype geometry with the inclusion of the 25mm internal waveguide of the power meter. The addition of the internal waveguide to simulation decreases both the average efficiency and the uniformity of efficiency across the entrance aperture.

3.2 Reduced transition length

As noted above, the efficiency of each geometry is determined primarily by the transition section while the Winston cone component controls the angular dependence. In search of a higher efficiency, a logical step is to reduce the length of the transition, thus limiting the reflection loss at its walls. Figure 7 shows the angular dependence of the 1-5 Winston cone geometry with varying transition lengths; it is immediately evident that shorter transition sections yield monotonically higher efficiencies. Closer inspection shows that most of the efficiency loss comes from rays that enter the transition section after reflections near the throat of the Winston cone section, as illustrated in Fig. 8. These "near-throat" rays enter the transition section at steep angles and experience numerous reflections within the transition section, whereas rays that reflect from locations in the Winston cone section that are farther from the throat enter -the transition section at shallower propagation angles. (These "near-throat" rays correspond to waveguide modes that are close to their cutoff frequencies.)

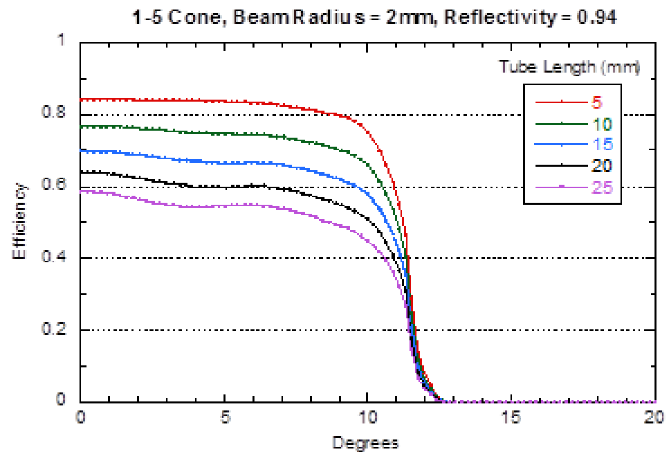

Figure 7: Transition-length dependence of the original 1-5 Winston cone geometry.

From these results, an obvious potential improvement is the "no-transition" geometry shown in Fig. 4. An additional design that is investigated is the "back-to-back" geometry, which uses a second, smaller Winston cone section as a transition from the initial Winston cone to the waveguide in an attempt to reduce the angle with which near-throat rays enter the rest of the system. Of course, such a back-to-back geometry only makes sense if the throat diameter is significantly less than the small waveguide dimension. This sets a lower frequency limit to the approach.

Figure 9 shows the spatial dependence of a geometry consisting of a 1-5 Winston cone section in conjunction with a 5mm transition section. While the efficiency of the geometry is greater than the efficiency of the identical, 25mm transition geometry, the efficiency is still not noticeably uniform over the entrance aperture to the Winston cone.

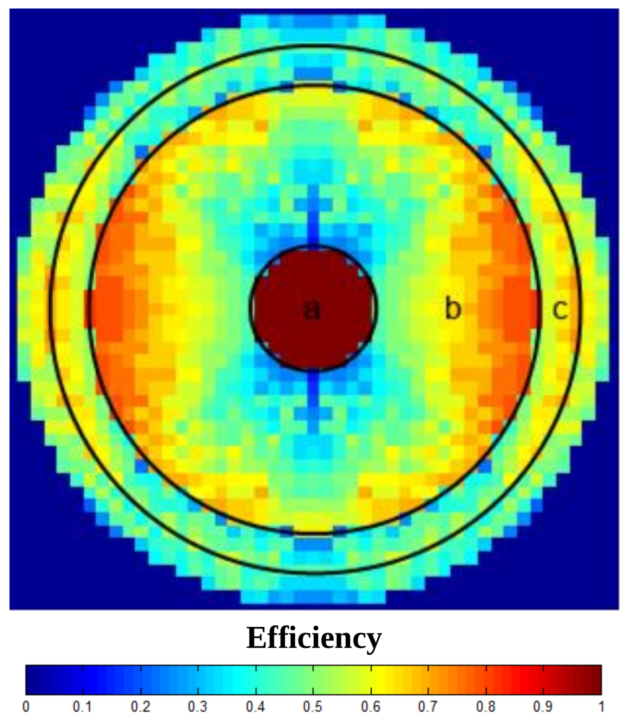

Figure 8: The 1-5 Winston cone with 25mm transition and internal waveguide at normal incidence (same as top left panel in Fig. 6.) Region (a) represents rays with zero reflections within the Winston cone. Rays in region (b) have one reflection; rays in region (c) have two. Rays that intersect the Winston cone near its throat ("near-throat" rays) have considerably lower efficiencies, as is shown by the innermost areas of regions (b) and (c)

3.3 No-transition geometries

The most obvious extension of the reduction of transition length is the removal of the transition section altogether. As shown above in Fig. 4, this geometry requires some modification of the Winston cone section in order to produce a rectangular aperture fit to the internal WR10 section of the power meter instead of the usual circular throat. This alteration was designed considering future prototype construction using electrical discharge machining: cuts are made into the back of the Winston cone and the front of a short waveguide section, which are then combined to create a flush but sharp transition between the Winston cone and the waveguide.

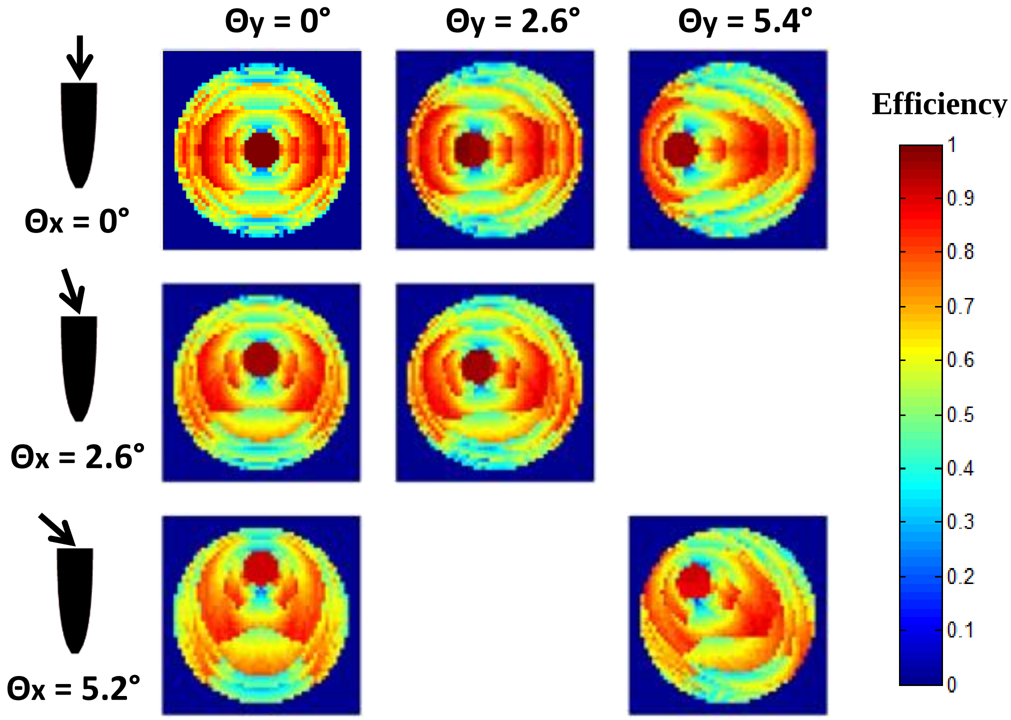

Figure 9: Spatial dependence of efficiency for the 1-5 Winston cone with a 5mm transition section. While average efficiency is increased from the 25mm transition model, the spatial dependence of efficiency is still considerably uneven.

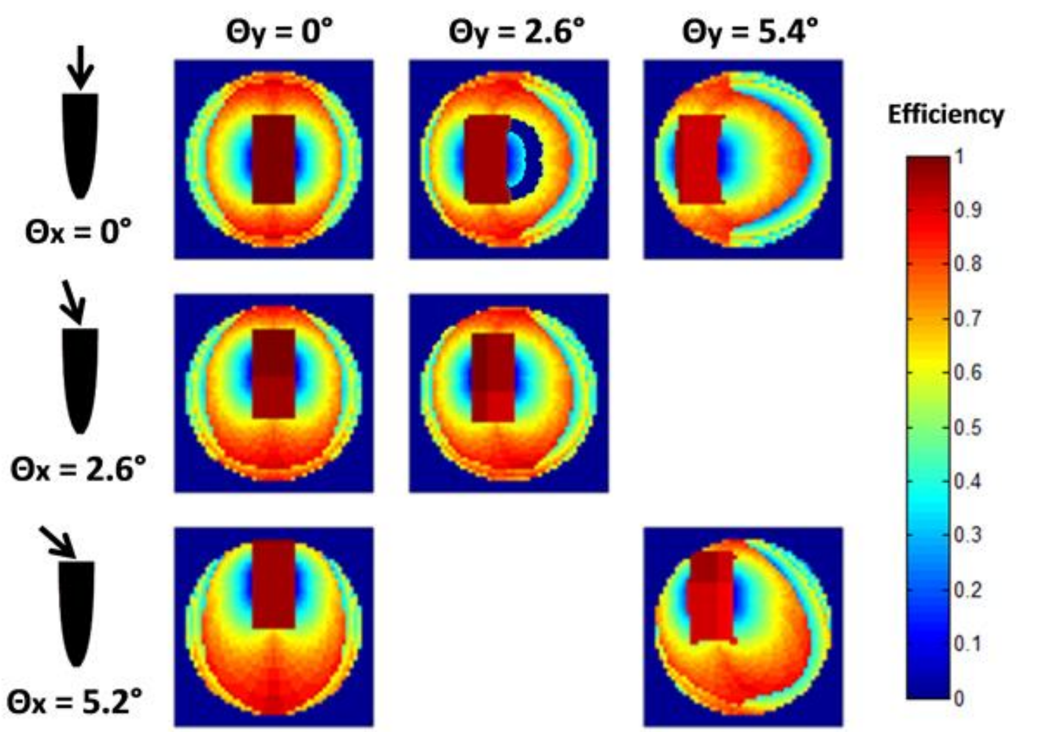

Figure 10: Spatial dependence of efficiency for the 1-5 prototype geometry without any transition section.

The most notable features of the resulting spatial dependence analysis (Fig. 10) are the rectangular shape of the straight-through section and the qualitative increase in spatial uniformity of efficiency over the entrance aperture. In previous geometries, the largest efficiency jump occurred between the straight-through rays and the set of near-throat rays that accumulated one bounce within the Winston cone section. In the no-transition geometry, a significant portion of the near-throat Winston cone is removed to allow for a smooth transition to the waveguide section, reducing the number of rays that experience near-throat reflections.

This geometric principle was employed on several other Winston cone of various input and throat diameters, producing similar results. For smaller Winston cone throat sizes on the order of 0.5mm, the waveguide cuts out larger areas of the near-throat rays, producing increasingly more uniform efficiency distributions. Decreasing the throat size, however, also decreases the angular range over which the Winston cone functions. (The acceptance angle for a 1-5 Winston cone is 11.5° whereas the acceptance angle for a 0.5-5 Winston cone with half the throat diameter is only 5.7°.)

3.4 Back-to-back geometries

The final new geometry to be presented in this paper is the back-to-back geometry described in Fig. 4. This design employs the geometric properties of the Winston cone in reverse to decrease the propagation angle of rays after they have been condensed by the initial Winston cone interface in order to limit the number of reflections that the near-throat rays encounter in the internal 25mm waveguide section. The reverse Winston cone transition section has a throat (here functioning as an entrance aperture) equivalent in size to the throat of the initial Winston cone section and an exit aperture with a diameter of 1.27mm that is completely enclosed by the rectangular waveguide section, eliminating the need for any further transition. Holding the entrance aperture of the Winston cone constant, the reverse Winston cone's length increases as the throat size of the initial Winston cone section decreases. This corresponds to a larger percent of near-throat rays that are captured and straightened by the reverse Winston cone section, leading to both a higher average efficiency and a greater uniformity of efficiency over the concentrator's entrance aperture. This concept is illustrated by Figures 11 and 12. It should be noted, however, that a reduced throat size not only corresponds to a shallower acceptance angle, but also introduces a sharp circular aperture within the concentrator geometry, for which physical optics effects cannot be ignored, especially at wavelengths large compared to the throat diameter. These back-to-back geometries are inherently a shorter wavelength approach than the no-transition geometries due to their smaller throat size.

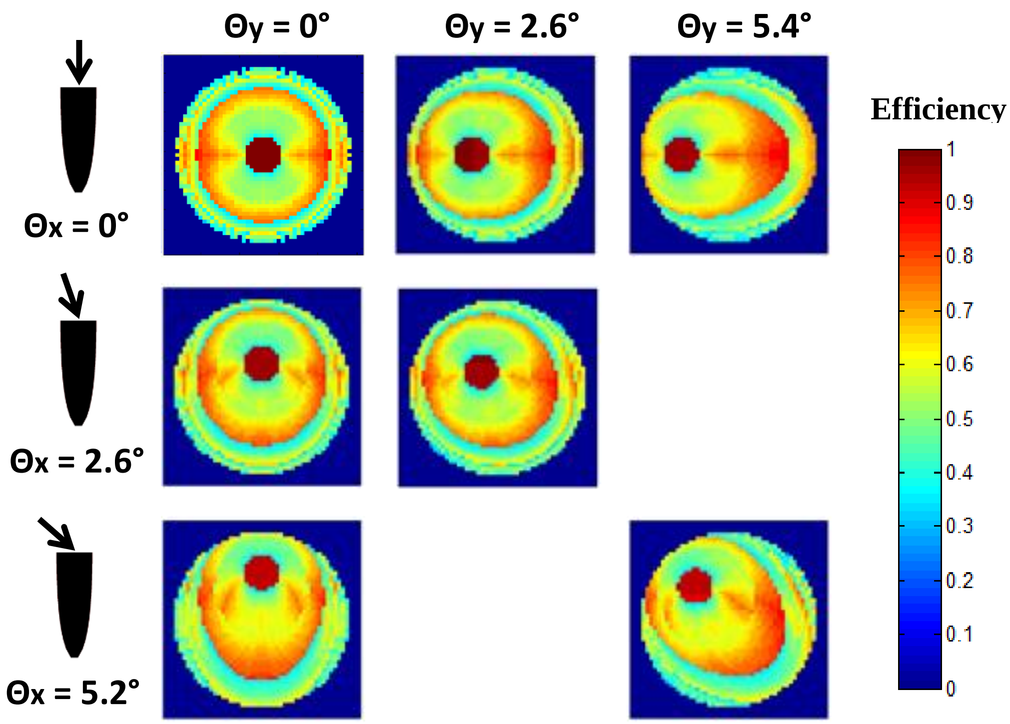

Figure 11: Spatial dependence of efficiency of the back-to-back geometry using a 1-5 Winston cone as the initial geometry.

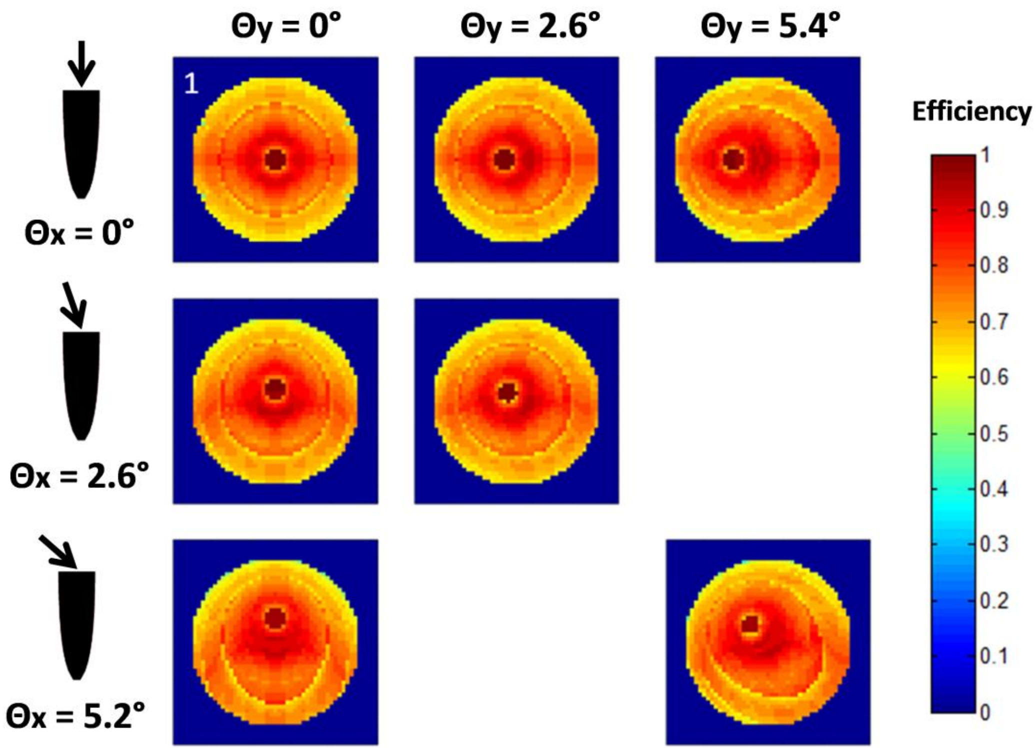

Figure 12: Spatial dependence of efficiency of the back-to-back geometry using a 0.5-5 Winston cone as the initial geometry. This geometry displays by far the most uniform and highest efficiency of any presented designs.

4. WAVELENGTH DEPENDENCE

A full and rigorous analysis of the wavelength dependence of the various geometries introduced above will be included in a future paper. However, a preliminary attempt to incorporate the effects of physical optics into the above simulations was conducted by applying a Gaussian smoothing filter to the geometric simulation results presented above. This analysis more closely resembles Winston cone analysis using an expanded He-Ne laser, as described in [11], rather than the 760 GHz analysis employed in [7].

The simulation results presented above display several unrealistically sharp variations in the spatial dependence of efficiency, as any real beam that would be used with these concentrators would be a weighted average over some finite area in the x-y plane. This would smooth out the above figures. While the most appropriate weighting or decomposition depends on the specifics of the application, for the purpose of illustrating the wavelength dependence of spatial uniformity, it is suitable to consider a Gaussian beam, which is focused (perhaps very weakly) to a beam waist that lies in the input plane of the Winston cone. This can be simulated by smoothing (convolving) the above geometric results with a Gaussian with a 1/e width proportional to $f\lambda$, which is the diffraction spot or Gaussian waist size. Figures 13, 14 and 15 show the geometric simulations presented above subject to Gaussian smoothing for

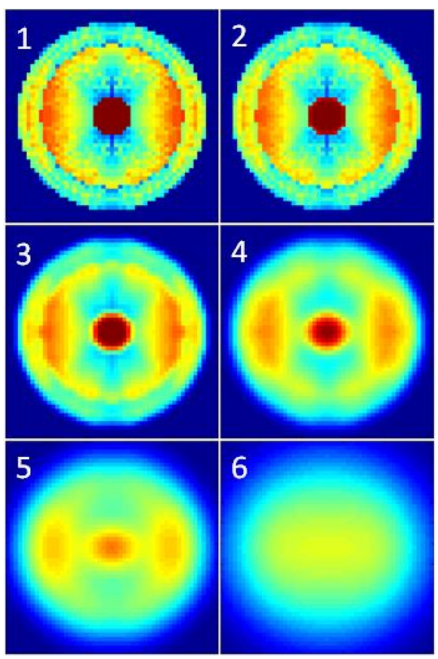

Figure 13: Gaussian smoothing on the 1-5 Winston cone. Plot 1 is the original geometric simulation. Plots 2 through 6 correspond to value of $f\lambda$ of 0.25, 0.5, 1, 2, and 4mm.

the three geometries presented in Fig. 4. These figures represent Gaussian smoothing for the following values of $f\lambda$: 0.25mm, 0.5mm, 1mm, 2mm, and 4mm. For a typical f/4 input beam, this corresponds to wavelengths of 0.0625, 0.125, 0.25, 0.5 and 1mm, respectively. For ease of display, only the normal incidence plots (upper-left corner of Figures 6, 10, and 12) are shown.

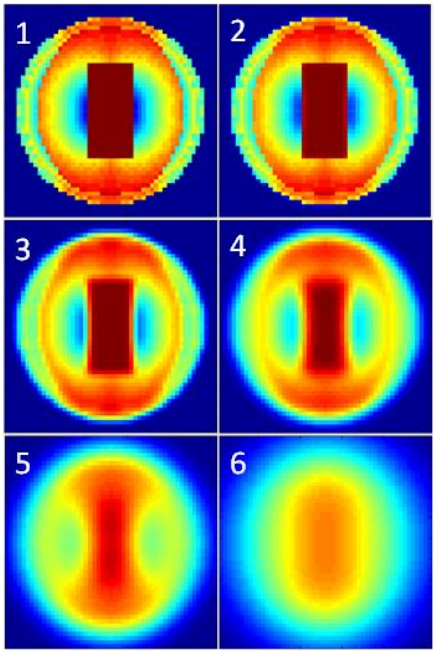

Figure 15: Gaussian smoothing on the no-transition geometry with a 1-5 Winston cone. Plot 1 is the original geometric simulation. Plots 2 through 6 correspond to values of $f\lambda$ of 0.25, 0.5, 1, 2, and 4mm.

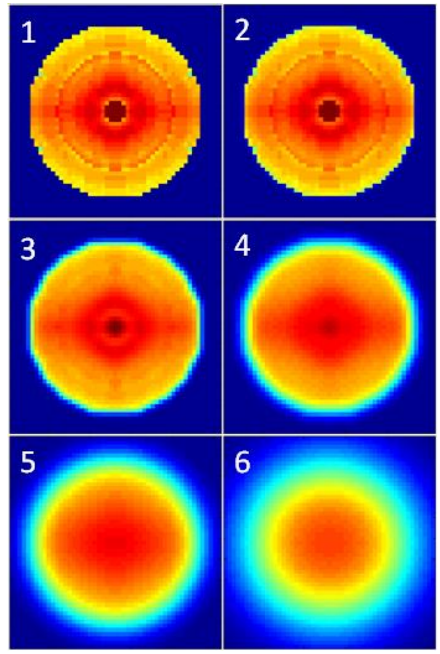

Figure 16: Gaussian smoothing on the back-to-back geometry with a 0.5-5 Winston cone. Plot 1 is the original geometric simulation. Plots 2 through 6 correspond to values of $f\lambda$ of 0.25, 0.5, 1, 2, and 4mm.

Comparing both the geometrical simulations and the above wavelength dependence, the two new designs (no-transition and back-to-back) emerge as the best candidates for future study, as they present both higher average efficiencies and more uniform spatial dependencies than the 1-5 Winston cone with a 25mm circular-to-rectangular transition section. It is well known, however, that light passing through an aperture with a diameter much less than its wavelength must be described by physical optics, and that the transmission rate decreases as λ/d increases, where d is the diameter of the aperture [12]. As the back-to-back configuration performs better with a smaller throat size, is suitable for use with smaller wavelengths. By contrast, the no-transition geometry optimizes efficiency at all throat sizes, making it applicable at larger wavelengths as well. Thus, these two designs cover the entire wavelength spectrum. A more rigorous analysis of the exact ranges that both designs cover will be included in a later report.

5. CONCLUSION

We have presented the design and simulation of three geometrical variations to prototype concentrators intended to convert submm signals between free space and overmoded, WR-10 waveguide. Concentrator geometries were analyzed for uniformity in the spatial dependence of efficiency over the entrance aperture of the Winston cone. Two designs emerged as promising leads for opposite ends of the wavelength spectrum: no-transition cones are suitable for longer wavelengths while back-to-back geometries perform better at shorter wavelengths. A more rigorous exploration of this wavelength dependence both in simulation and measurement will be presented in a later study. The current study has significant implications for submm power metrology. It demonstrates that this type of concentrator can indeed be used to couple between free space and overmoded waveguide with high and accurately know efficiency, and that modifications can be made to the basic Winston cone design to improve spatial uniformity and efficiency.

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