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Beamsplitting using self-imaging

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ABSTRACT

The production of a variable array of optical point sources from a single point source can be achieved through the self-imaging properties inherent in a rectangular waveguide. Two prototype devices, based upon this concept, were designed and constructed. The resulting output patterns are discussed along with future design considerations and applications.

Keywords: self-imaging, rectangular waveguides, beamsplitting, optical arrays.

1. INTRODUCTION

The production of multiple beams from a single beam can be accomplished through the self-imaging properties inherent in a rectangular waveguide. The multiple virtual images produced as a result of reflections within the rectangular waveguide[1] can be collected and focused into a compact bundle of diverging beams. With the cooperation of Tuan Vo Dinh, David Landis, and Oak Ridge National Laboratories, this technology is being applied to the field of Health Physics. Assisting their research with DNA sequencing[2], self-imaging beamsplitters have been employed to replace the optical masks often required in multiple sample DNA fluorescence testing. These beamsplitters provide a simplified, precise, and efficient means of illumination[3].

What follows is a brief mathematical explanation of how these multiple beams are formed along with a discussion of the experimental results and their application to an improved self-imaging beamsplitter design.

2. MATHEMATICAL DEVELOPMENT

As light enters a rectangular waveguide from a diverging source(see Fig. 1), the number of internal reflections experienced is dependent on the waveguide dimensions as well as the angle of divergence for the source.[4]

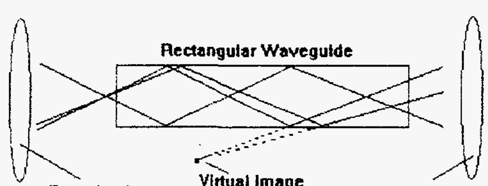


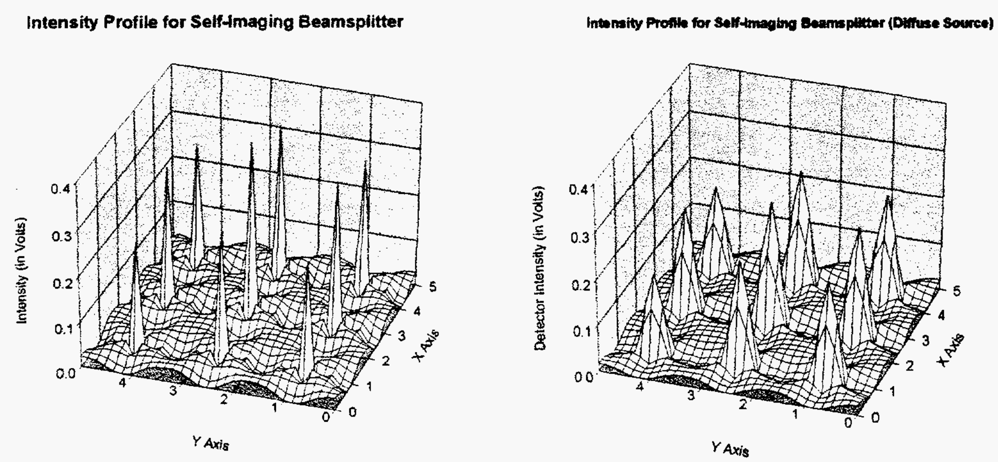
Fig. 1. Self-imaging schematic.

As is illustrated in Fig. 1, each internal reflection creates a virtual image which can be focused to a point with the aid of a lens. The total number of points produced is $(2n+1)^2$, where n is the number of internal reflections. This can quickly be deduced if one considers the rectangular waveguide to be a set of two orthogonal pairs of mirrors, each producing 2n virtual images. Since we have two sets of mirror pairs, then we will produce a total of $(2n)^2$ virtual images for the rectangular configuration. In addition, a central spot resulting from unreflected rays, and 4n spots produced due to the divergence occurring at the corners of the waveguide, must be included in our calculations, giving $(4n^2 + 4n + 1)$ imaged points. Consequently, factoring this equation we arrive at $(2n + 1)^2$ focused spots. The spacing between each focused spot is dependent upon the waveguide width, the distance of the source to the focusing lens, and the magnification of the focusing lens.

It can easily be seen that the number of reflections occurring within the waveguide can be altered by adjusting either the dimensions of the waveguide or the distance between the waveguide and the source[5].

3. EXPERIMENTAL RESULTS

The output beams produced by a variety of self-imaging rectangular waveguides were measured. First, a nine beam pattern was produced using a red HeNe laser focused with a microscope objective into the end of a 25 x 2.36 x 2.47mm rectangular quartz waveguide and collected via a 25mm focal length spherical lens. What resulted was a pattern with a large central beam intensity surrounded by eight slightly lesser beams (Fig. 2a). Each beam was capable of being focused to a fine point within an area measuring roughly 5mm by 5mm. This area could easily be changed by either altering the collecting lens-to-waveguide distance or by changing the lenses focal length. This system, however, required precise alignment to produce the expected number of output beams with misalignment resulting in an uneven intensity distributed and/or "double vision."



(a) *(b)*

Fig. 2. Graphs reveal the differences in intensity profiles for an uncoated rectangular waveguide with focused source (a) and a silver coated rectangular waveguide with a diffuse source (b).

In an attempt to reduce the critical alignment required of the first system, a .5mm pinhole mask was centered and attached to the optical entrance of the waveguide. A diffuser was then brought into contact with the mask and illuminated by the source (see Fig. 3). What resulted was a system which was always aligned regardless of the direction or location of the illuminating source and was, therefore, alignment free. In addition, the

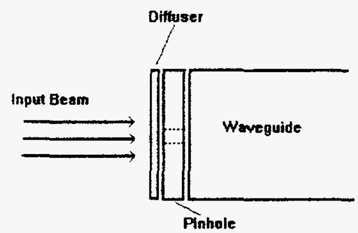


Fig. 3. Alignment-free design.

waveguide was coated with silver to reduce the amount of light lost upon reflection. This produced a pattern which had a 30% lower peak intensity then the first system's pattern and with a slightly more

Fig. 4. Pattern produced from a silvered waveguide with diffuser.

uniform intensity distribution over its nine beams (Fig. 2b & 4). However, since the diffuse source was an extended object (.5mm diameter) as opposed to the focused point source of the first system, it was noted that the beams could not be focused to as small of a point as had been done previously.

Experiments were also performed regarding the possible variations in waveguide dimensions. As expected, it was found that smaller cross section rectangular waveguides produced a larger amount of output beams for a given input angle.

The best choice of collecting lenses was also qualitatively analyzed. It was observed that spherical lenses produced a noticeable distortion in the focused beams, due to a variety of optical aberrations. This effect was greatly reduced by using shorter focal length aspherical lenses.

4. DESIGN DETAILS

Possible designs for the production of a *standard* multiple output beamsplitter, which could be easily interfaced with a variety of light sources, were considered. A prototype system was developed which used a 1 mm silica gel fiber optic cable as the input source for a silvered rectangular quartz waveguide. The optical fiber as well as the waveguide were mounted in two holes centered with one another which had been drilled into a 2" long plastic cylinder. An aspherical lens of short focal length was also mounted in a larger hole, also centered with the waveguide, and used to collect and focus the output

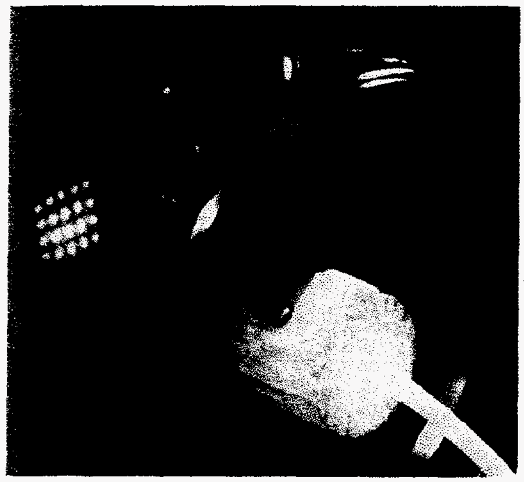


Fig. 5. Compact self-contained beamsplitter (prototype #1).

beams. The resulting design was a device which was unaffected by alignment, efficient, simple and inexpensive to produce, and easily customizable (see Fig. 5). This compact beamsplitter was 97% efficient in splitting the beam diverging from the 1 mm core fiber.

As expected, changing the core diameter, or the numerical aperture, of the optical fiber produced a change in the diameter of the focused spots. Therefore, a second device was constructed which allowed the optical fiber to be connected via an SMA connector, thus allowing the optical fiber's core diameter to be easily varied. This second device was constructed out of aluminum (1.5" length, .5" diameter) and was designed so that the output lens was adjustable. A smaller uncoated quartz waveguide (25 x 1.5 x 1.5mm) was used to produce a total of 49 output beams with high efficiency.

5. FUTURE GOALS

Future plans involve designing a third prototype which is capable of an even greater number of output beams with an increased uniformity in intensity. Experiments involving birefringent materials and intentional misalignment will also be conducted to determine advantages of "double vision." An ongoing attempt will also be made in every design, to create systems which result in as flexible and versatile a device as is possible.

In addition, the possibility of using the self-imaging rectangular waveguide beamsplitter as a four faced surface plasmon biosensor will be investigated. Preliminary experiments indicate that it is possible to coat each face of a rectangular waveguide with a thin metal island film, which when used as a beamsplitter, produces a 3 x 3 array with intensities dependent upon the opto-electronic coupling at the surface of each face. Therefore, each face would act as an individual sensor with a corresponding focused spot in the 3 x 3 array. The central spot, which does not correspond to any surface, would serve as a reference for this four-sensors-in-one device. These possibilities and others will be considered as possible applications of the self-imaging beamsplitter.

6. ACKNOWLEDGMENTS

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