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Ball Lens Reflections by Direct Solution of Maxwell's Equations

R. P. Ratowsky, L. Yang, R. J. Deri,
J. S. Kallman, and G. Trott

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R. P. Ratowsky , L. Yang[1], R. J. Deri,
J. S. Kallman, and G. Trott[1]

Lawrence Livermore National Laboratory
Livermore, California 94551

[1]Hewlett-Packard Laboratories
Palo Alto, California 94303-0867

1. Introduction

Ball lenses are important for many applications. For example, ball lenses can be used to match the mode of a laser diode (LD) to a single mode fiber (SMF), essential for low-loss, high bit rate communication systems. Modeling the propagation of LD light through a ball lens presents a challenge due to the large angular divergence of the LD field (typically > 20° HWHM) and the subsequent significant effect of spherical aberration. Accurately calculating the reflected power is also difficult, but essential, since reflections as small as -30 dB can destabilize the LD. [1]

A full-wave analysis of this system using, e.g., a finite-difference time-domain method is not practical because of the size of the ball lens, typically hundreds of wavelengths in diameter. Approximate scalar methods [2] can give good results in some cases, but fail to calculate reflected power and miss polarization effects entirely.

Our approach exploits the fact that the scattering of an arbitrary electromagnetic beam from a sphere is an exactly solvable problem. The scattering of a plane wave from a sphere is a classical problem which was solved by Mie in 1908 [3]. More recently, various workers have considered the scattering of a Gaussian beam from a sphere [4] and its numerical implementation for other applications. To our knowledge, this is the first time this approach has been applied to a problem in optical design. We are able to calculate reflection and transmission accurately with modest computational effort.

2. Method

We assume the ball lens is a perfect, homogeneous sphere, and that departures from ideality can be modeled by a suitable average over lens radius or wavelength. An LD or SMF mode is modeled as an approximately linearly ($\hat{\mathbf{x}}$) polarized (possibly astigmatic) Gaussian beam of vacuum wavelength l . In the waist plane $z=-z_0$ it has the form

$$E_x(x,y;z=-z_0)=E_0\exp\left(-(x-x_0)^2/\sigma_x^2-(y-y_0)^2/\sigma_y^2\right),$$

where x_0, y_0 are offsets from the optical (z) axis. We need to know the field everywhere outside the lens, which can be written as the sum of the incident field and a scattered field:

$$\mathbf{E}_{out}=\mathbf{E}_{inc}+\mathbf{E}_{scat}.$$

The scattering problem is solved by a vector multipole expansion of the incident (LD or SMF), scattered and internal fields. Details of this expansion, which involve some subtle convergence issues for wavelength scale LD spot sizes, will be presented at the conference. Satisfying the boundary conditions at the surface of the lens (the continuity of $\hat{\mathbf{r}} \times \mathbf{E}$ and $\hat{\mathbf{r}} \times \mathbf{H}$) determines the field everywhere. In practice we employ a T-matrix method to calculate the expansion coefficients of the field [3]. We require typically ~1000 terms in the expansion for a convergent result. Once the field is known we can calculate overlap integrals of interest. For example, the power reflected back to an optical fiber is $R = \iint \mathbf{E}^*_{inc} \cdot \mathbf{E}_{scat}\, dxdy$, where the integral is over the plane of incidence $z = -z_0$.

3. Results

To validate our method, we have calculated the back reflection to a SMF of mode size 4.5 μm (half-width at $1/e^2$ intensity) at various lens-fiber distances for two different ball lenses: 250 μm sapphire (n = 1.75) and 300 μm BK-7 (n = 1.5). In all cases the fiber is on the optical axis. The light wavelength is 1.3 μm. The back reflections were also measured experimentally. These results are shown in Fig. 1; it is apparent that the calculation agrees with experiment in most cases to better than 1 dB.

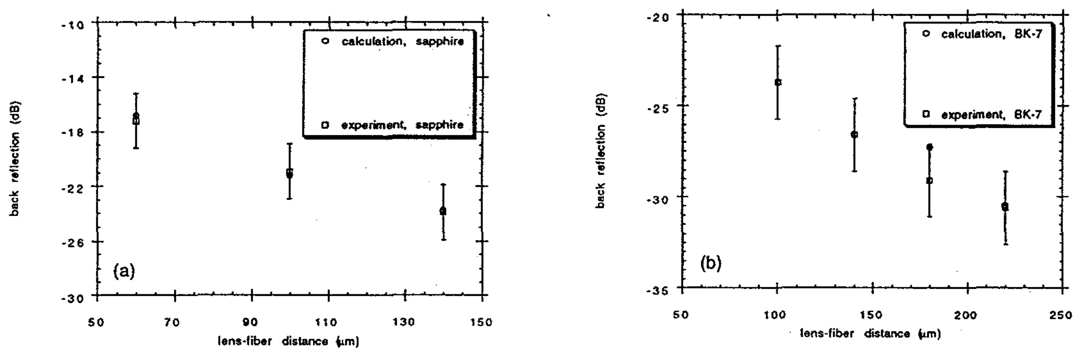

Fig. 1. (a) Back reflection to SMF from (a) 250 mm radius sapphire lens; (b) 300 mm radius BK-7 lens

The SMF results give us confidence to calculate the back reflection to an LD, where measurements are much more difficult to make. In Fig. 2 we show the back reflection to an LD of symmetric spot size $(1.22\ \mu m)^2$ as the LD-lens distance is varied. Note the nonmonotonic behavior, probably due to high-order resonances in the spherical lens.

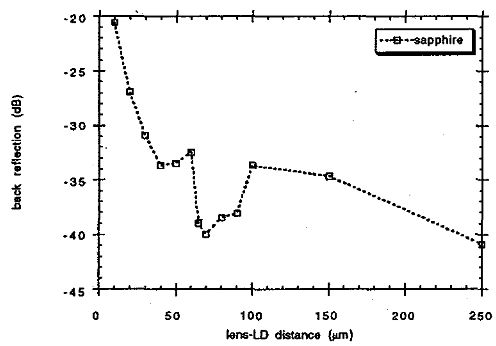

Fig. 2 Back reflected power to a LD for a 300 mm radius ball lens.

Our results clearly indicate that we are able to predict accurately the reflection from a ball lens to a SMF. We believe our method can accurately predict the back reflection for the LDs which is very difficult to make reliably using any other existing method. The LD calculations are very difficult to make reliably using any other method. This technique will additionally allow us to study the effect of misalignments, and the extension of the method to antireflection coated lenses is straightforward. Calculations of coupling to optical fibers will also be forthcoming.

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