

Phase and amplitude apodization induced by focusing through an evanescent gap in a solid immersion lens microscope

Joshua S. Jo
 Tom D. Milster, FELLOW SPIE
 J. Kevin Erwin
 Optical Sciences Center
 Optical Data Storage Center
 Tucson, Arizona 85721
 E-mail: joshua.jo@quantum.com

Abstract. We characterize phase and amplitude apodization induced when a converging beam passes through an evanescent gap. The apodization is caused by vector transmission and reflection properties. General characteristics are described for solid immersion lens indices from $n_{\text{SIL}} = 1.5$ to 3.1, gap heights from $h = 0$ to 300 nm, and marginal ray angles $\alpha_m = 0.7$ or 0.84, where α_m is the direction cosine of the marginal ray angle inside the solid immersion lens. A small amount of defocus is found to be a good compensator of the phase apodization for low n_{SIL} and h . After proper defocus is applied, asymmetry of focus in the spot may remain, primarily due to the uncompensated amplitude apodization. Simplification of the phase and amplitude characteristics is accomplished by applying a Jones-matrix expansion to the transmission coefficient through the gap. Simulation and experiment quantify the effect with a simple solid immersion lens geometry. © 2002 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1485999]

Subject terms: SIL; aberration; evanescent coupling; diffraction; polarization; near-field optics.

Paper 010067 received Feb. 26, 2001; revised manuscript received Feb. 4, 2002; accepted for publication Feb. 4, 2002.

1 Introduction

The extension of microscopy, data storage, and other applications to resolve ever smaller features motivates the use of evanescent microscopes,¹ in which evanescent coupling across a small gap is used to improve resolution. The vector nature of evanescent coupling induces certain phase and amplitude apodizations that can influence the performance of the optical system. In this paper, we quantify the apodization and describe its effects for scanning solid immersion lens (SIL) microscopes. For the SIL system introduced by Mansfield and Kino,¹ the last lens is a hemisphere centered on the image, as shown in Fig. 1. The effective numerical aperture inside the SIL is $\text{NA}_{\text{EFF}} = n_{\text{SIL}} \text{NA}_{\text{AIR}} = n_{\text{SIL}} \alpha_m$, where α_m is the direction cosine associated with marginal ray. For scanning microscopes, a focused laser beam illuminates the sample through the objective lens and SIL. The reflected light is collected through the same lens system.

Since resolution is proportional to $\lambda/\text{NA}_{\text{EFF}}$, improved resolution is observed for high n_{SIL} and large θ_m . However, when $\text{NA}_{\text{EFF}} > 1$, the beam coupling through the air gap becomes partially evanescent. The sample must be in proximity to the SIL in order for the evanescent energy to couple through the gap. The $1/e$ decay distance $z_{1/e}$ of the evanescent energy at the marginal ray angle is given by

$$z_{1/e} = \frac{\lambda}{4\pi} \frac{1}{(\text{NA}_{\text{EFF}}^2 - 1)^{1/2}} \quad (\text{NA}_{\text{EFF}} > 1). \quad (1)$$

For example, if $\lambda = 633$ nm and $\text{NA}_{\text{EFF}} = 1.3$, we have $z_{1/e} \approx 0.15\lambda = 61$ nm.

The formulation of the electric field using high-NA focusing into layered media was introduced by Ichimura et al.,² who based their calculations on the work of Richards and Wolf.³ Our theoretical development is based on the application of the Debye⁴ approximation in a high-NA imaging system, which differs from that of Ichimura et al.² in that the total electromagnetic field can be calculated in any plane of the recording layers, as well as the reflected field.

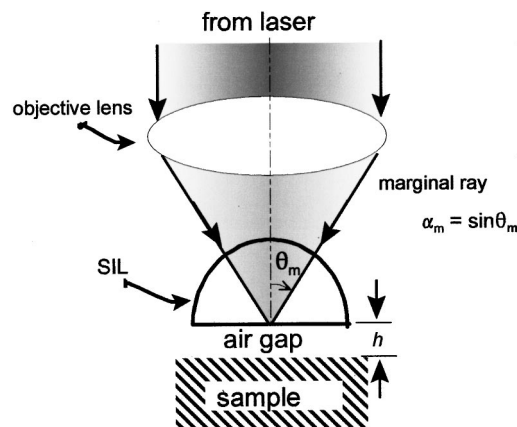


Fig. 1 A simple solid immersion lens (SIL) geometry. A laser beam focuses on the bottom of the SIL. A small air gap h separates the SIL and the sample.