Direct measurement of laser power through a high numerical aperture oil immersion objective lens using a solid immersion lens

Shigeki Matsuo and Hiroaki Misawa
Faculty of Engineering, The University of Tokushima, 2-1 Minamijosanjimacho, Tokushima 770-8506, Japan

(Received 11 October 2001; accepted for publication 8 February 2002)

For many laser applications, information on irradiated laser power is important. However, direct measurement of laser power through a high numerical aperture objective lens is difficult in a laser microscope. In this article, we propose a method which use a solid immersion lens (SIL) for such measurements. A laser beam focused by an objective lens is introduced to the flat surface of a SIL, emitted through the spherical surface, and then detected. In this way the divergence of the laser beam is reduced, and as a result the detection efficiency of the laser power increases. From theoretical analysis, a Weierstrass-sphere type SIL was found to be an appropriate thickness for this propose. Transmittance of the SIL is evaluated for several refractive indices. The validity of this method is confirmed experimentally. © 2002 American Institute of Physics.

I. INTRODUCTION

Laser microscopes are widely used in the fields of microspectroscopy, confocal imaging, three-dimensional photolithography, optical recording, etc. A common feature of laser microscopes is high spatial resolution. Spatial resolution is represented by the numerical aperture (NA), defined as NA = n sin θmax, where n is the refractive index of a medium between the objective lens and the sample, and θmax is the maximum incident angle. With a high NA objective lens, high spatial resolution is achieved. Another characteristic of a laser microscope is high photon density. Due to high photon density, a nonlinear optical effect (multiphoton phenomenon) is frequently induced at the focal point of a laser microscope. This is significant when an ultrashort pulse laser is used as a light source.

One basic parameter of laser applications is irradiated laser power. This is important especially for the nonlinear optical phenomena. However it is difficult to measure irradiated laser power at the focus of a laser microscope through a high NA (>1) objective lens. Let us suppose a simple case; a coverslip is put at the stage of the laser microscope, as shown in Fig. 1(a). In this case, a beam with a large incident angle (NAb = n sin θ > 1; solid line) undergoes total internal reflection (TIR) and does not transmit to the air at all. For a beam of NAb ≤ 1 (dashed line), part of the incident beam passes through the coverslip, but the divergence is too large to measure the power using the usual power meter, in addition, the reflection at coverslip–air boundary is not negligible.

One method for the power measurement is as follows. First, the laser beam path of the laser microscope is aligned. Then the objective lens is substituted by a diaphragm whose aperture diameter is the same as that of the objective lens, and laser power through the hole Pdiam is measured. The transmittance of the objective lens at the laser wavelength \( T_{\text{obj}} \) is measured separately. The power at the focus is calculated as \( P_{\text{diam}} \times T_{\text{obj}} \). Misawa et al. have proposed a dual-objective technique for the measurement of \( T_{\text{obj}} \) and measured the laser power for laser trapping and laser ablation precisely. This method gives a correct value. However, since the method is not a direct measurement, the intrinsic character of the particular objective lens (e.g., degradation of optical coatings) and the particular beam alignment could not be taken into account. In addition, this method requires a specially manufactured diaphragm for each objective lens, which is not available commercially.

The goal of this article is to propose a method for the laser power measurement through a high NA objective lens. The method should be (1) direct (measure the laser power which really passed the objective lens), (2) convenient for practical use, and (3) correct within an error of a few percent. We propose a method using a solid immersion lens (SIL). An analysis for the appropriate thickness of the SIL and for the transmittance of the SIL is presented. The validity of the method proposed is demonstrated experimentally.

II. THEORETICAL ANALYSIS

A. Basic concept

The SIL technique was first proposed by Mansfield and Kino to improve the spatial resolution of the optical microscope. A SIL is a spherical lens (diameter of 2r, refractive index of \( n_{\text{SIL}} \)) which is polished to a thickness of \( r \) [hemisphere type; H-type] or \( (1 + 1/n_{\text{SIL}})r \) [Weierstrass sphere (W-type) or hyperhemisphere type]. Usually, a SIL is used with a dry objective lens. The flat surface of the SIL is attached to a sample. Then the sample is observed through the SIL. The NA of the whole system is increased by \( n_{\text{SIL}} \) times. Applications of the SIL technique include high-density optical data storage, high-resolution imaging, lithography, and spectroscopy.

Our idea is to use a SIL for the measurement of laser...
power through a high-NA objective lens, shown in Fig. 1(b). The sample is replaced by a SIL attached to a coverslip. A laser beam is focused onto the center of the flat surface of the SIL and emitted through the spherical surface, then the laser power is measured. If we use a W-type SIL whose refractive index is equal to or larger than that of the coverslip, the power is measured. If we use a W-type SIL whose refractive index is equal to or larger than that of the coverslip, the power is measured. If we use a W-type SIL whose refractive index is equal to or larger than that of the coverslip, the power is measured. If we use a W-type SIL whose refractive index is equal to or larger than that of the coverslip, the power is measured. If we use a W-type SIL whose refractive index is equal to or larger than that of the coverslip, the power is measured.

Figure 1(b) might give the impression that this method is applicable only to inverted-type microscopes, but not to upright microscopes. This is not the case. In fact, this method is applicable to upright microscopes if one adheres the coverslip and the SIL with optical adhesive. The adhesion also helps to remove the air gap between the coverslip and the SIL which may interfere with the transmission of light.

**B. Appropriate thickness of the SIL**

The two thicknesses of SIL mentioned above, \( r \) and \( \left( 1 + 1/n_{\text{SIL}} \right) r \), are the only thicknesses that are of free aberrations. For the present purpose, aberrations are acceptable. Figures 1(c) and 1(d) show examples. Figure 1(c) describes a SIL that is much thinner than a W-type SIL. The divergence angle \( \delta \) was not reduced satisfactorily. Figure 1(d) shows a SIL much thicker than a W-type one. The divergence angle \( \delta \) was significantly reduced, but a beam with a large incident angle undergoes TIR.

With regard to the two problems above, we applied two criteria for the thickness of the SIL.

(a) Maximum divergence angle \( (\delta_{\text{max}}) \). Small \( \delta_{\text{max}} \) is preferable for full detection of the power. The value allowable depends on the shape of the power meter. For most of commercial power meters, \( \delta_{\text{max}} = 25^\circ \) seems to be small enough. For some power meters, \( \delta_{\text{max}} = 45^\circ \) or even larger could be detected. From this criterion, the minimum thickness of the SIL, \( z_{\text{min}} \), is calculated.

(b) Maximum angle of refraction at the SIL–air surface \( (\gamma_{\text{max}}) \). Small \( \gamma_{\text{max}} \) results in a small reflection at the SIL–air surface. The condition "TIR does not occur" corresponds to \( \gamma_{\text{max}} = 90^\circ \). Large \( \gamma_{\text{max}} \) yields a large reflection even if TIR does not occur, so under severe conditions \( \gamma_{\text{max}} \) may be set smaller than \( 90^\circ \), for example, \( 60^\circ \). This criterion gives the maximum thickness of the SIL, \( z_{\text{max}} \).

These two criteria are schematically shown in Fig. 2.

The calculated values for \( n_{\text{SIL}} = 1.517 \) and 1.845 with \( \gamma_{\text{max}} = 90^\circ \) and \( 60^\circ \) and \( \delta_{\text{max}} = 25^\circ \) and \( 45^\circ \) are shown in Table I. Details of the calculation are described in the Appendix. As can be seen in Table I, for less severe criteria \( \delta_{\text{max}} = 45^\circ \) and \( \gamma_{\text{max}} = 90^\circ \), a SIL with \( n_{\text{SIL}} = 1.845 \) has a large compatible range, i.e., \( z_{\text{min}} < z_{\text{max}} \). A SIL with \( n_{\text{SIL}} = 1.517 \) also has a compatible range around the thickness of a W-type SIL, but this range is much smaller than that of \( n_{\text{SIL}} = 1.845 \). For the severe criteria \( \delta_{\text{max}} = 25^\circ \) and \( \gamma_{\text{max}} = 60^\circ \), a SIL with \( n_{\text{SIL}} = 1.517 \) does not have a compatible range \( (z_{\text{min}} > z_{\text{max}}) \). In contrast, a SIL with \( n_{\text{SIL}} = 1.845 \) will still have a compatible range, and the compatible range includes the thickness of a W-type SIL. These calculations indicate that a SIL with \( n_{\text{SIL}} = 1.845 \) could be used under most con-

**TABLE I.** The minimum and maximum thicknesses of SIL normalized by thickness of the Weierstrass sphere

<table>
<thead>
<tr>
<th>( n_{\text{SIL}} )</th>
<th>( z_{\text{min}}/r )</th>
<th>( z_{\text{max}}/r )</th>
<th>Thickness of the Weierstrass sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.845</td>
<td>0.522</td>
<td>0.118</td>
<td>0.619</td>
</tr>
<tr>
<td>1.517</td>
<td>0.709</td>
<td>0.586</td>
<td>0.619</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.659</td>
</tr>
</tbody>
</table>
ditions, and that the thickness of the W-type SIL is appropriate. A SIL with \( n_{\text{SIL}} = 1.517 \) could not be used under severe conditions, but under less severe conditions (i.e., smaller NA or larger \( d_{\text{max}} \)), it could be used. It should be pointed out, however, that a SIL with \( n_{\text{SIL}} = 1.517 \) has an attractive feature: the refractive index is almost the same as that of the commonly used coverslip and immersion oil. Thus a SIL with roughly polished flat plane is applicable for the measurement without significant scattering.

**C. Reflection loss**

In general, a boundary between different refractive index materials causes the reflection of light. In the present method, reflection at the two boundaries, coverslip/SIL and SIL/air, may cause an error in the power measurements. Therefore, we have evaluated the transmittance of these boundaries. The reflectance (polarization averaged) was calculated as a function of \( N_A = n \sin \theta = n_{\text{SIL}} \sin \alpha \). The calculations were carried out for W-type SILs with refractive indices of \( n_{\text{SIL}} = 1.517 \) and 1.845, respectively, and a coverslip with a refractive index of \( n_{\text{cover}} = 1.517 \).

The results are shown in Fig. 3. As is seen, the total transmittance is almost constant in the \( N_A < 1 \) range, about 95.8% and 90.3% for \( n_{\text{SIL}} = 1.517 \) and 1.845, respectively. In the \( N_A > 1 \) range, the transmittance decreases with an increase in \( N_A \). The average transmittance for the whole beam (all the \( N_A \) range) \( T_{\text{ave}} \) was calculated assuming (i) \( N_A = 1.4 \), (ii) the spatial distribution of power is flat (not Gaussian), and (iii) the distance between the center optical axis and the beam path is proportional to \( \sin \theta \). The calculated value \( T_{\text{ave}} \) was 94.0% and 89.0% for \( n_{\text{SIL}} = 1.517 \) and 1.845, respectively. For most cases assumptions (i) and (ii) should overestimate the influence of the high-\( N_A \) range, and thus underestimate \( T_{\text{ave}} \). However the error is no more than 2%, which is small enough.

Another possible source of error is the incident angle dependence of the detection efficiency of a power meter. Usually, the detection efficiency of a power meter decreases with an increase in incident angle. This angle dependence is not significant for thermal-type power meters. However, for photodiode-type ones, the dependence is not negligible. Unfortunately, the angle dependence is not identical, so this aspect should be considered in individual instruments. Recent advances in antireflection technology by microstructuring the Si surface will help the development of angle independent photodiodes.

**III. EXPERIMENTAL RESULTS**

To demonstrate the validity of this method, laser power through a high-NA objective lens was measured with and without a SIL as a function of the input beam diameter. The setup is shown in Fig. 4. A frequency-doubled continuous wave (cw) Nd:YAG laser (532 nm) was used as a light source. The laser beam was expanded enough to fill the aperture of an objective lens and then the beam was reflected by a dichroic mirror (DM570), and focused by an objective lens (PlanApo 60×oil, NA = 1.4). A SIL attached to a coverslip, or just a coverslip, was placed at
The authors thank Professor H. Akiyama (University of Tokyo) for providing the SIL and for fruitful discussions and Dr. S. Juodkazis for critical reading of the manuscript. This work was partly supported by a Grant-in-Aid for Encouragement of Young Scientists (Grant No. 12750221) from the Japan Society for the Promotion of Science, and by the Satellite Venture Business Laboratory of the University of Tokushima.

APPENDIX: CALCULATION OF \( z_{\text{min}} \) and \( z_{\text{max}} \)

The relationships of the angles \( \alpha, \beta, \gamma, \delta, \) and \( \epsilon \) are

\[
\alpha + \beta = \epsilon,
\gamma + \delta = \epsilon,
\]

\[
n_{\text{SIL}} \times \sin \beta = \sin \gamma. \tag{A1}
\]

For calculation of \( z_{\text{min}} \) and \( z_{\text{max}} \), \( \alpha \) is determined by the NA to be

\[
\alpha = \alpha_{\text{max}} = \sin^{-1}(\text{NA}/n_{\text{SIL}}). \tag{A2}
\]

Line \( l \) in Fig. 2 is expressed as

\[
z - r \cos \epsilon = \frac{1}{\tan \alpha} (x - r \sin \epsilon). \tag{A3}
\]

Thus, if \( \epsilon \) was obtained, we can calculate the \( z \) intercept as

\[
z(x=0) = \frac{\cos \epsilon - \sin \epsilon}{\tan \alpha}. \tag{A4}
\]

Note that \( z_{\text{min}} \) and \( z_{\text{max}} \) have signs opposite to that of the \( z \) intercept by definition.

For the case of criterion (a) (Sec. II B), \( \delta = \delta_{\text{max}} \) is a given value. By substituting \( \beta = \epsilon - \alpha \) and \( \gamma = \epsilon - \delta_{\text{max}} \) into Eq. (A1), we obtain

\[
n_{\text{SIL}} (\sin \epsilon \cos \alpha - \cos \epsilon \sin \alpha) = \sin \epsilon \cos \delta_{\text{max}} - \cos \epsilon \sin \delta_{\text{max}},
\]

and expanding this,

\[
\sin \epsilon (n_{\text{SIL}} \cos \alpha - \cos \delta_{\text{max}}) = \cos \epsilon (n_{\text{SIL}} \sin \alpha - \sin \delta_{\text{max}})
\]

is obtained. Rearranging this, we obtain the following expression for \( \epsilon \):

\[
\epsilon = \tan^{-1} \left( \frac{n_{\text{SIL}} \sin \alpha - \sin \delta_{\text{max}}}{n_{\text{SIL}} \cos \alpha - \cos \delta_{\text{max}}} \right). \tag{A5}
\]

The value of \( z_{\text{min}} \) is calculated by substituting Eq. (A5) into Eq. (A4).

For the case of criterion (b) (Sec. II B), \( \gamma = \gamma_{\text{max}} \) is given, thus

\[
\beta = \sin^{-1} \left( \frac{\sin \gamma_{\text{max}}}{n_{\text{SIL}}} \right). \tag{A6}
\]

Then, by substituting \( \epsilon = \alpha + \beta \) into Eq. (A4) and expanding, we obtain

the sample’s position. The SIL used was a W-type SIL made of LaSF9 (\( n_{\text{SIL}} = 1.845, r = 0.5 \text{ mm} \)), polished by Ogura Jewel Industry Co., Ltd., which was attached to a coverslip with optical adhesive (NOA68, Norland; \( n = 1.54 \)). The focus of the laser beam was set to the top surface of the coverslip. The output power was measured by a calibrated detector (818-UV/CM, Newport). The inset of Fig. 4 shows the dimensions around the SIL. The laser power at the entrance of the microscope was measured with a Si photodiode (S2281, Hamamatsu).

The power measured is shown as a function of beam diameter \( d \) in Fig. 5(a). As is seen, the power detected with the SIL was higher than that without it for all values of \( d \). In addition, the difference increased with an increase in \( d \). These results show that the detection efficiency was dramatically improved by using the SIL, as expected.

Figure 5(b) shows the transmittance (the power at the sample’s position divided by that at the entrance) with and without a SIL as a function of \( d \). As is seen, the transmittance with the SIL was constant in the small \( d \) range, about 79% up to 6 mm. Taking into account the transmittance of the objective lens and the reflectance of the dichroic mirror (about 90±2% and 99%, respectively, measured by us), we conclude that almost 89% of output through the objective lens was detected by the present method. This value is consistent with the transmittance of 89% expected (Sec. II C). This agreement indicates the validity of the present method. In contrast to this, the transmittance measured without the SIL was lower and decreased monotonously with an increase in beam diameter. It is impossible to deduce valuable information from the power measured without the SIL.

FIG. 5. Incident beam diameter dependence of the (a) power and (b) transmittance.
\[
\frac{\varepsilon_{\text{max}}}{r} = \cos(\alpha + \beta) - \frac{\sin(\alpha + \beta)}{\tan \gamma} = -\frac{\sin \beta}{\sin \alpha}. \quad (A7)
\]

By substituting Eqs. (A2) and (A6) into Eq. (A7),

\[
\frac{\varepsilon_{\text{max}}}{r} = -\frac{\sin \gamma_{\text{max}}}{\text{NA}}. \quad (A8)
\]

It should be pointed out that the value of \( \varepsilon_{\text{max}} \) is independent of \( n_{\text{SIL}} \).

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2. In this article, \( \text{NA}_b = n \sin \theta \) is defined for a small portion of incident beam, while \( \text{NA} = n \sin \theta_{\text{max}} \) is defined for the entire incident beam.
18. For different \( n_{\text{SIL}} \), the average transmittance are 93.3%, 91.8%, 89.9%, 87.9%, and 85.8% for \( n_{\text{SIL}} = 1.600, 1.700, 1.800, 1.900, \) and 2.000, respectively.