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High-Power Laser Beam Transfer through Optical Relay Fibers for a Laser Guide Adaptive Optics System

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Abstract

We are developing a laser guide star adaptive optics (LGSAO) system for the Subaru Telescope on Mauna Kea, Hawaii. The AO188 system will dramatically increase the observable sky area. This system differs from systems used at other large telescopes in that it utilizes the combination of an all-solid-state mode-locked sum-frequency generation (SFG) laser as a light source and single-mode optical fiber for beam transference. Optical fibers transfer laser light from the source, located at the Nasmyth platform, to the laser launching telescope more flexibly and more easily than do mirror relay optics. However, optical fibers induce nonlinear scattering effects, such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), beyond certain threshold levels in high-power lasers. We measured the laser transmission characteristics of a photonic crystal fiber (PCF) whose mode field diameter (MFD) was 11 μm, and a step index fiber (SIF) cable whose MFD was 4.2 μm to evaluate the threshold levels for non-linear effects. We observed SRS in the 200-m-long SIF when we input 1.3 W. However, SRS and SBS were not induced in the 200-m-long PCF, even for an input power of 5.3 W. As a result, we estimated the threshold of SRS to be 33 W for the 35-m-long PCF designed for the Subaru LGSAO system. Given that the fiber will carry a laser beam of about 30 W with a pulse width of less than 1 ns, we conclude that nonlinear scattering will pose no problems for this application.

Key words: instrumentation: adaptive optics, atmosphere effects, laser guide star, optical fiber

1. Introduction

One method for creating a laser guide star (LGS) takes advantage of the presence of a layer of sodium atoms that are deposited by meteors at a height of $\sim$90 km in the upper atmosphere. a laser tuned to the D_2 transition at 589.159 nm is used to excite the sodium atoms. The light emitted when the excited sodium atoms return to the ground state forms a bright spot that can be used as an artificial guide star for adaptive optics. The sodium layer has a thickness of about 10 km; thus, range gating is not necessarily required to select the backscattering range. Both pulsed and continuous-wave (CW) lasers can be used to create sodium guide stars as long as the laser is launched along the optical axis of the main telescope to reduce the side-looking effect.

A new adaptive optics system with a 188 sub-aperture curvature wavefront sensor and a bimorph deformable mirror (AO188) was developed for the Subaru Telescope (Iye et al. 2004; Oya et al. 2006; Takami et al. 2006). Whereas the first generation adaptive optics system (AO36: Takami et al. 2004) with 36 sub-apertures achieved a Strehl ratio of 0.35 in the K-band under the best seeing ($0\farcs4$), the AO188 is expected to deliver a Strehl ratio of 0.65 in the K-band and a diffraction-limited image core in the J band under average seeing conditions. The AO188, which includes the LGS system, also significantly improves the sky coverage. The sky coverage of AO36 was limited to a few percent or less at the K-band due to the limited number of available bright guide stars. The LGS system will essentially solve the difficulty of finding bright guide stars.

The LGS system is one of the most important subsystems in the AO188. The system consists of the following components (Hayano et al. 2006): a 5.3-W quasi-CW mode-locked sum-frequency generation (SFG) laser whose wavelength is tuned at 589.159 nm; diagnostics systems for monitoring the power, quality, polarization, and exact wavelength of the laser beam; a beam transfer system using a solid cored photonic crystal fiber (PCF); and a laser launching telescope with an aperture diameter of 50 cm (LLT). Figure 1 shows the layout of the entire Subaru LGS system.

The SFG laser specifications are listed in table 1. The requirements for the laser source include sufficiently high power, accurately controlled wavelength and bandwidth, high beam quality, and controllable polarization. If the laser performance fails to satisfy any of these requirements, the LGS generated in the upper atmosphere will not be sufficiently bright. Generating a bright LGS requires not only sufficient power, but also good beam quality and proper bandwidth (1.7 GHz). Although the optimum bandwidth of the laser should be slightly narrower than 2.06 GHz, it does not significantly affect the brightness of the LGS.

1.1. LGS System Laser and Laser Relay Optics Choices

As noted above, a key feature of our LGSAO system is the adoption of optical fiber to relay the laser beam from the Nasmyth platform where the laser source is installed to the LLT mounted at the backside of a secondary mirror of the Subaru Telescope. This arrangement requires a 35-m-long optical fiber.

In fact, the laser beam can be transferred either by a mirror train or by an optical fiber. Only the Subaru Telescope and Very Large Telescope (VLT) use optical fiber for the LGS system (Bonaccini et al. 2004). An optical fiber relay has some advantages compared to a mirror relay (see table 2). First, it is easier to maintain good beam quality with an optical fiber relay than with a mirror relay. Single-mode fiber delivers a good transverse electromagnetic mode (TEM_{00}) and attains a beam quality index (M^2 factor) as small as 1.0 for an optical fiber relay system. Second, the optical fiber can be easily and flexibly deployed around the main telescope. In our system, a laser room has been constructed on the Nasmyth floor to provide a stable environment for the laser source, and the LLT is installed on the optical axis behind the secondary mirror. The two key components are easily linked with optical fiber. However, a fiber relay has some shortcomings compared to a mirror relay. First, the input laser beam must be precisely aligned to the optical fiber to ensure optimum efficiency. This requires positioning the optical fiber and the coupling lens with an accuracy of 0.1 μm. In the case of an optical fiber whose mode field diameter (MFD) is 14.3 μm, the transmission efficiency decreases by 0.1% for every 0.1-μm shift in each position. Second, silica, the fiber material, attenuates the light. The loss due to the fiber's material is typically 10 dB km^{-1}, corresponding to 0.35 dB for a 35-m fiber. Third, and most important, unlike mirrors, optical fibers cannot relay high-power laser beams due to induced nonlinear effects. High-energy density at the core generates nonlinear effects, especially stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). An evaluation of these nonlinear effects is described later.

To conclude, we selected an optical fiber rather than a mirror train, considering the advantages in ease of deployment and improved beam quality to be more important than the shortcomings.

Laser transfer systems are not common among large telescopes. The Keck observatory started science observations with LGSAO in late 2004. The Keck LGS system uses a dye laser as a light source, operated in the Q-switched pulse format at a repetition rate of either 13 or 26 kHz (van Dam et al. 2006; Wizinowich et al. 2006). The output of the dye laser is sent out to the sky through a projection telescope with a 50-cm-diameter output lens, mounted on the side of the main telescope. Mirrors and lenses transfer the high-power laser beam, and the laser is typically operated at an output power of between 12 and 14 W. This system generates a LGS with a typical equivalent V magnitude of 9.5 to 10.5 mag at the zenith. As the laser is launched from the side of the main telescope, the LGS image is elongated. Its typical FWHM is $1''.6 \times 2''.4$.

An LGSAO system, Altair, installed on Gemini North Telescope saw first light in 2005 (Richardson et al. 1998; Boccas et al. 2006). This laser system is a solid-state 12-W

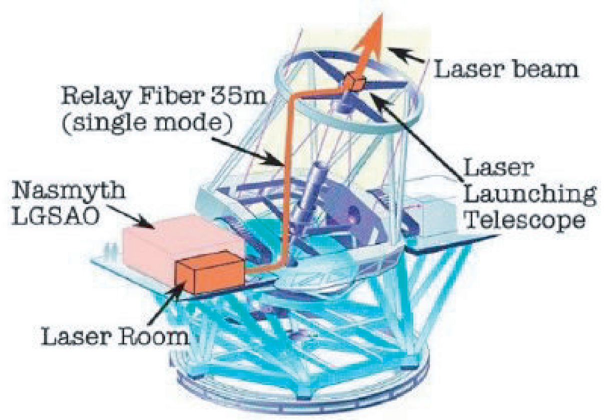

Fig. 1. Layout of the Subaru Telescope LGS system.

Table 1. Specifications of 589 nm SFG laser.

Wavelength	589.159 nm
	(Tunable from 589.060 to 589.170 nm)
Output laser power	> 5 W
Oscillation	Mode-locked pulse
	(Repetition rate: 143 MHz)
Bandwidth	1.7 GHz
Pulse width	0.7 ns
Beam quality	TEM_{00}, $M^2 < 1.03$
Polarization	linear (horizontal)
Power stability	$\pm$ 1.3 %

Table 2. Merits and demerits of a fiber relay and a mirror relay.

	Mirror train	Fiber relay
Beam quality	difficult to keep beam quality	single mode output
Flexibility of transfer	complex mirror control	flexible to transfer
Maximum power to transmit	high power is transmittable	nonlinear effects of fiber
Transmission loss	high reflectance of mirror	material loss of fiber

589-nm laser utilizing sum-frequency technology operated in 75-MHz mode-locked pulse format. The laser has a 500-MHz bandwidth and is tuned to the center of the sodium D_2 line. The LGS brightness is equivalent to $V \sim 9$ mag. Mirrors and lenses are used to relay the laser beam to the LLT, mounted behind the secondary mirror of the Gemini Telescope. The LGS size is $1''.5$ to $1''.8$ FWHM, at best.

ESO has been developing an LGS system for the VLT to serve the AO instruments NAOS-CONICA and SINFONI (Bonaccini et al. 2004). Their dye laser delivers > 10 W of CW power on a 20-MHz bandwidth, or a LGS with $\simeq 9$ mag in the V band after beam conditioning. They adopted a 27.5-m-long, single-mode optical fiber for the laser relay. The laser bandwidth is broadened via an electro-optic modulator to avoid nonlinear effects (Bonaccini et al. 2003). This is the world's first use of an optical fiber relay for LGS. The ESO LGS requires stable throughput above 70% and uses a PCF with a 14-μm MFD.

Note that our laser type is similar to that of Gemini, and our laser transfer system is similar to that of the ESO system.

1.2. Optical Relay Fiber Candidates

Our SFG laser has a power of about 5.3 W with good beam quality. Therefore, we require a single-mode optical relay fiber that can transmit such a high-power laser beam while maintaining its quality.

Step index fiber (SIF) is the most common optical fiber in this category. SIF has a double structure, core and cladding, whose refractive indices are slightly different. Although it is widely used, the MFD of the SIF has a problematic limitation. To enlarge the MFD of the SIF, it is necessary to reduce the difference between the refractive indices of the core and cladding. However, this increases light loss due to fiber bending, and reduces the transmission efficiency. Consequently, we turned to PCF, which has a larger MFD. PCF is a new category of optical fiber that derives its waveguide properties, not from a spatially varying material composition, but from an arrangement of very tiny air holes ($\sim 5\,\mu$m) running along the fiber axis.

An advantage of PCF is that it can be made with larger cores (10–17 μm) than those of the SIF (at most $\sim 5\,\mu$m). The larger core size permits a lower energy density at the fiber core, suppressing any nonlinear scattering effect. Adjusting the laser beam to the PCF has also been simplified. However, a treatment of the PCF fiber end is difficult because the air holes need to be collapsed so as to avoid any damage to the fiber. Expense and complexity of manufacturing are other disadvantages.

Recently, another type of PCF appeared that is capable of maintaining a polarization state of the beam passing through it. It has two larger air holes beside the core region. Photonic bandgap fibers (PBG fibers) are another new possibility; these possess a completely different guiding mechanism, based on the photonic bandgap of the cladding region. This mechanism even allows guidance in a hollow core (i.e., in a low-index region). Such air-guiding photonic crystal fibers can have a very low nonlinearity and a high damage threshold. However, we cannot use these fibers, as they are expensive and still under development. Consequently, we used a solid-core PCF that lacked a polarization-preserving function for our experiments.

The purpose of this research was to address the question of whether the PCF is useful for relaying a high-power laser beam, while avoiding any nonlinear effects that might hinder the use of SIF. In the next subsection, we describe the nonlinear effects in the optical fiber.

1.3. Stimulated Nonlinear Effects in Optical Relay Fiber

Lasers can generate very high-intensity light, resulting in several nonlinear effects, the most important of which are parametric nonlinearities in certain crystal materials, the Kerr effect, Raman scattering, Brillouin scattering, saturation of gain or optical losses, and two-photon absorption. The parametric nonlinearities give rise to effects such as frequency doubling, sum- and difference-frequency generation, and parametric amplification. The Kerr effect increased the refractive index by an amount that is proportional to the intensity, and leads to effects such as self-focusing, self-phase modulation, and four-wave mixing. We focus primarily on SRS and SBS because these effects are more important for an optical fiber relaying a high-power laser beam. The other effects were negligible in our experiments.

The nonlinear response of a transparent optical medium to the intensity of the light propagating through the medium is very fast, but not instantaneous. In particular, a non-instantaneous response is caused by vibrations of the crystal (or glass) lattice, i.e., Raman scattering. This can be described quantum mechanically as the scattering of a photon by a molecule to a lower-frequency photon, since the molecule makes the transition to a vibrational state (Agrawal 2007). When the intensity of the generated frequency-shifted radiation, the Stokes wave, becomes sufficiently high, that wave may again act as a pump for further Raman scattering. The most significant feature of Raman scattering in silica fibers is that its gain extends over a large frequency range (up to 40 THz) with a broad peak located near 13 THz.

Brillouin scattering is an effect caused by the nonlinearity of a medium, specifically, by that part of the nonlinearity that is related to acoustic phonons. An incident photon can be converted into a scattered photon of slightly lower energy, usually propagating in the backward direction, and a phonon. This can occur spontaneously even at low optical power and can become a strong stimulated effect above a certain threshold power of in a given medium. Above that threshold, SBS can reflect back most of the power of an incident beam. This process can create a strong optical gain for the back-reflected wave, with a typical bandwidth of 50- to 100-MHz for silica fibers. The frequency of the reflected beam is slightly lower than that of the incident beam; the frequency difference corresponds to the frequency of the emitted phonons. This so-called Brillouin frequency shift, which is set by a phase-matching requirement, is typically in the gigahertz range (e.g., about 10–20 GHz for silica fibers), depending on the material composition, the optical frequency, and to some extent on the temperature and pressure of the medium. SBS can easily occur in optical fibers, and can limit the potential of a single-frequency fiber laser to generate a high output power, or simply to limit the potential of a fiber to transmit a narrow-band light beam. To increase the Brillouin threshold, we must increase the

Table 3. Specifications of fibers for nonlinear experiment.

#	Fiber type	Manufacturer	MFD [μm]	Length [m]	Transmission efficiency [%]	Attenuation [dB km^{-1}]
1	PCF	Mitsubishi Cable Industries, Ltd.	11	200	40	10
2	SIF	Nufern	4.2	200	40	6.4

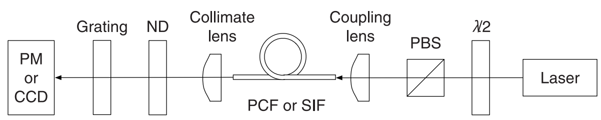

Fig. 2. Experimental setup for SBS and SRS threshold measurements. Laser, our SFG laser; λ/2: half-wave retarder; PM, power meter; PBS: polarized beam splitter; ND, ND filter.

bandwidth, of the laser beyond the Brillouin gain bandwidth, or reduce the fiber length. The major difference between SRS and SBS is that SRS is associated with optical phonons, whereas SBS is associated with acoustical phonons.

Generally, the threshold of the SRS, P_{SRS}, is defined as

$$P_{\mathrm{SRS}} \simeq \frac{16A_{\mathrm{eff}}}{g_{\mathrm{R}}L_{\mathrm{eff}}}, \tag{1}$$

and that of the SBS, P_{SBS}, is defined as

$$P_{\mathrm{SBS}} \simeq \frac{21A_{\mathrm{eff}}}{g_{\mathrm{B}}L_{\mathrm{eff}}}, \tag{2}$$

where A_{eff} and L_{eff} are the effective aperture and the effective fiber length, respectively, g_{R} is the Raman gain (in the case of fused silica, $\sim 2\times10^{-13}\,\mathrm{m\,W^{-1}}$) and g_{B}, the Brillouin gain, is $\sim 5\times10^{-11}\,\mathrm{m\,W^{-1}}$ (Agrawal 2007). Consequently, the longer is the fiber, or the smaller is the fiber core, the lower is the threshold level.

SBS nearly ceases for short pulses whose width is less than 1 ns in general (Agrawal 2007). However, the pulse width of our SFG laser is 0.7 ns, making it difficult to predict the threshold of nonlinear scattering under such a transitional condition. Therefore, we must examine both SRS and SBS.

2. Experimental Methods

The coherent light source was developed and manufactured by Megaopto Co., Ltd. to generate an LGS at the sodium layer. The source was achieved by sum-frequency generation mixing of 1064- and 1319-nm beams emitted from actively mode-locked Nd:YAG lasers. The two wavelengths were combined in a nonlinear optical crystal. The performance of the source was tested before the experiment. The source produced $\sim$5.3 W with a bandwidth of about 1.7 GHz tuned to the sodium D_2 line at 589.159 nm and a Gaussian beam profile of TEM_{00}. Because the source output stability was approximately $\pm$ 1.3% over 8 h of operation, we neglect the power fluctuation. Hereafter, we call this source our SFG laser.

Figure 2 shows the experimental setup. The optical fibers used are listed in table 3. Because we had to measure specific nonlinear scattering thresholds, we employed a SIF and a PCF as long as 200 m, nearly 6-times longer than the actual length needed for our system, to lower the threshold to within the measurable range.

Laser power was controlled by a half-wave plate and polarized beam splitter (PBS). To couple the laser beam with the fiber, we used aspheric lenses, whose focal lengths were 13.8 mm and 35 mm for SIF and PCF, respectively. a grating (NT43-005; Edmond optics) passed the output beam through the fibers. We controlled the position of the coupling lens and the fiber edge with an accuracy of 0.1 μm. As a result, the transmission efficiency, including the coupling efficiency and the optical fiber throughput, was about 40% in the SIF and the PCF. In other words, a total of the material loss in the fiber and the coupling loss is equivalent to a transmission loss, and it was about 60%. As shown in table 3, the attenuation of the SIF was 6.4 dB km^{-1}, corresponding to a throughput of 74% for a 200-m fiber. Therefore, the coupling loss for the SIF was about 34%. Attenuation in the PCF could not be measured due to its particular edge. Table 3 lists the specification value for PCF attenuation. The throughput of the PCF was estimated to be 63%, and then the coupling loss to be about 23%. This PCF did not have a polarization-preserving function; the size and pitch of the air holes were optimized for the wavelength of the sodium D_2 line.

3. Results

When the power input to the SIF exceeded about 1.3 W (0.5 W through the SIF given the transmission efficiency), scattered light appeared (figure 3). Beyond this SRS threshold level, the scattered light increased progressively. Figure 4 presents the scattered light spectrum for an input power of 4 W, showing two peaks: one at 589 nm and the other at 606 nm. The reflected light at 589 nm included the reflected light at the fiber end and at other optical components, whereas the light at 606 nm was caused solely by nonlinear scattering. Because the amount of the Raman shift exceeded 10 nm, SRS was likely to occur in the SIF. However, SBS features, which might appear in the backscattered light, were not detected. As a result, the threshold of SRS for the SIF was confirmed to be $\sim$0.5 W for a 200-m test fiber.

In contrast, we were not able to see SRS or SBS for the test PCF at the injected laser powers of less than 5.3 W, corresponding to 2.1 W transmitted (see figure 5). Therefore, neither scattering threshold was confirmed for the PCF. The most critical difference between the PCF and the SIF was the MFD, i.e., the effective aperture. The PCF had an MFD of about three-times larger than that of the SIF, so that, in terms of the cross-section, the threshold level for nonlinear scattering would be nine-times higher. In a precise sense, we cannot apply

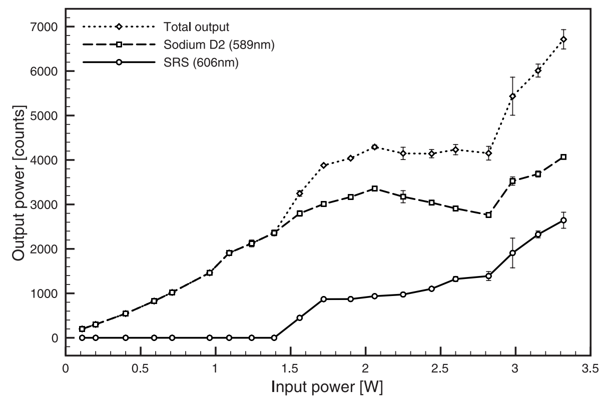

Fig. 3. Output counts from the SIF. Solid line, dashed line, and dotted line show the SRS counts, un-scattered light, and total, respectively.

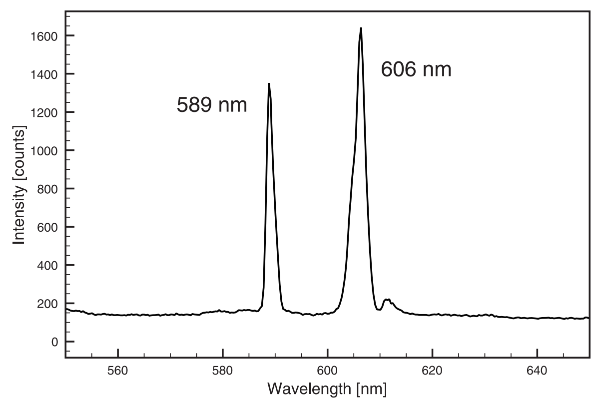

Fig. 4. Spectrum of the backscattered light returned from the SIF as a function of wavelength for a 2-W laser beam input and transmission efficiency of $\sim 40\%$. Two peaks appear, one at 589 nm, the other at 606 nm.

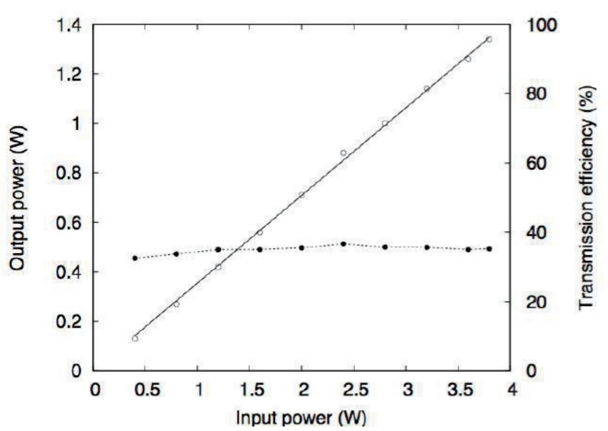

Fig. 5. Open circle represents the output power, which increases proportionately with the input power in the PCF. No nonlinear scattering appears. The transmission efficiency is represented by filled circles.

this simple geometrical conversion to estimate the threshold of the PCF because Raman gain and the fiber attenuation behave differently in the two fiber types.

4. Discussion

Although SRS was detected in the SIF, at our laser power (about 2.1 W), SBS was not. SBS is not clearly apparent for our quasi-CW, 143-MHz mode-locked, 0.7-ns pulse width SFG laser. The transient theory of SBS states that a laser whose pulse width is narrower than the lifetime of the acoustic phonon (≈ 16 ns) lowers the Brillouin gain (Kroll 1965). Our result is consistent with that theory. SRS occurs more easily than SBS for our SFG laser.

We are approaching our eventual laser power goal of 10 W. Therefore, we needed to determine whether the PCF could transfer a laser beam at output powers of up to 10 W. For this experiment, we used a 200-m-long PCF with an 11-μm MFD. In actual operation, the fiber is 35-m long with a 14.3-μm MFD. We chose a PCF with a smaller MFD to create stimulated nonlinear effects more easily. Equations 1 and 2 show that the threshold level of the PCF intended for actual use is about nine-times higher. Consequently, we concluded that the PCF will not exhibit stimulated nonlinear scattering, even when we upgrade the laser power to 10 W.

Here, we propose a more elaborate numerical evaluation of the threshold value. Given that SRS occurred at ~ 0.5 W for a SIF with an MFD of 4.2 μm and a length of 200 m, we calculated that SRS would appear in a 35-m-long SIF at 2.9 W, considering the 200/35 factor, and would not be appropriate for 10-W operation. We estimated the threshold of forward SRS for a PCF as being about 33 W, considering that in the PCF, the MFD is 14.3/4.2 times larger and assuming that the SRS process is similar in SIF and PCF. In addition, we calculated the threshold of SRS numerically using equation (1). We used an effective area, $A_{\mathrm{eff}} = 14.3^2\pi\ \mu\mathrm{m}^2$ and an effective length, $L_{\mathrm{eff}} = 33.7$ m. The effective length was calculated while assuming that the transmission loss of the PCF was 10 dB km^{-1}. The constant in equation (1) is 16, from the forward SRS. Our calculations yielded a threshold of 80 W. This differs by a factor of 2.4 from the presumed threshold value of 33 W based on experiments. The difference may be considered to be the result of the approximation included in equation (1).

In conclusion, our PCF will not exhibit nonlinear scattering, even with an extremely high-power SFG laser beam (over 30 W) input. This indicates that laser beam transfer by PCF could become a mainstream practice if a higher-power mode-locked SFG laser becomes available in the future.

5. Summary

We are developing an LGSAO system for the Subaru Telescope, by adopting an optical fiber instead of a mirror train, to relay the high-power laser beam from the laser source at the Nasmyth platform to the Laser Launching Telescope (LLT) mounted on the backside of the secondary mirror of the main telescope.

Since nonlinear effects, especially stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), are known to be practical limiting factors for optical fibers transmitting high-power laser light, we measured the threshold levels of these effects for two types: a step index fiber (SIF) and a photonic crystal fiber (PCF), each 200-m long. We observed SRS in the SIF at a transmitted laser power of 0.5 W, whereas neither SRS nor SBS was observed in the PCF at transmitted powers of up to 2.1 W. From these measurements, we estimated that the SBS threshold for the actual 35-m long PCF in our LGSAO system to be 33 W or larger. Our laser upgrade plan assumes an operating power of 10 W, well below this threshold. Hence, relaying a high-power laser-beam with a PCF fiber will provide easy deployment and a high-quality beam without negative nonlinear effects. This indicates that laser-beam transfer by PCF could become a mainstream practice if a higher-power mode-locked SFG laser is used in the future.

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