Optical Phase Conjugation for Removing Small Space Debris

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Small space debris removal using phase conjugate light (PCL) was proposed. Required PCL energy for deorbiting debris rotating in the low-earth orbit was estimated to be several kilojoules. A flash-lamp pumped Nd:YAG resonator was used as a phase conjugator to achieve a simple-structured, all-optical debris tracking and pointing system. PCL generation was succeeded and its time-reversal property was demonstrated. Introducing MOPA system was discussed to be an effective way to increase PCL energy without losing beam quality.

Key Words: Optical Phase Conjugation, Space Debris Removal, Saturable-gain Four-wave Mixing

1. Introduction

The growing amount of debris in space poses a long-term threat to sustainability in space development. 1) For large debris, spacecrafts can maneuver away from the debris path in danger of collision because large debris is catalogued and their paths can be estimated in advance. Various measures such as electrodynamic tether technology 2) are also presently being studied to deorbit large debris. However, debris smaller than several centimeters is neither catalogued nor monitored; therefore, although collision with small space debris can cause serious damage to spacecrafts, avoiding the danger of collision is difficult.

Removing small space debris using a high-energy laser is one proposed solution; 3,4) illumination of a high-energy laser beam from an orbiting laser satellite on the target debris induces laser ablation. The generated plasma jet provides momentum to the debris, which changes debris orbit and the debris then drops into earth’s atmosphere. For this scheme, target debris three-dimensional location is required in advance so that laser beam can be focused on the debris. Beam steering techniques have mostly been studied using gimbal-based systems. 5-7) However, using rotating stages makes the system slow, bulky, heavy, and power consuming. Generated torques also affects satellite attitudes. Non-mechanical optical beam-steering methods have also been studied, 8-10) but they usually have small aperture size and are not suitable for high power operation. Wavefront correction mechanism is not intrinsic to those beam steering methods; diffraction limited focusing is not achieved and energy loss is inevitable because of wavefront distortions caused by passing through distorted optical surfaces and thermal lenses in amplifiers. Adaptive optics is a technique to correct wavefront distortions, but this technique is costly and complicated because it requires a guide star, wavefront sensor, deformable mirror and its feedback control. 11)

For this problem, the automatic targeting and pointing capability of phase conjugate light (PCL) can be used. Optical phase conjugation is a technique that reverses direction of beam propagation while maintaining the same wavefront. 12) A light beam reflected by the phase conjugator precisely retraces its original light path and hits its light source. PCL can be emitted in real-time with no mechanical control or wavefront measurement because the generation process is completely optical. Therefore, when light from small space debris hits the phase conjugator equipped in a satellite, PCL will be automatically generated and travel back the incident light path, and focus a nearly diffraction limited beam on the moving debris achieving high power density. Because PCL travels as if signal light was going back in time, PCL is sometimes called time-reversed light.

In this study, a flashlamp-pumped Nd:YAG rod placed in a laser oscillator is used for the phase conjugator. Target-reflected laser output and the light traveling back and forth in the laser cavity interfere and modulate the gain in the rod, diffracting light which becomes PCL. Using the rod as both a laser gain material and as a phase conjugator, and re-using the target-reflected laser beam as a signal beam enable the system to be maximally-simplified because no additional light source is required.

2. Small Space Debris Removal Using Optical Phase Conjugation

All-optical laser focusing on moving small space debris can be achieved as shown in Fig. 1. The scenario is first, detecting debris by illuminating relatively large area with an expanded laser beam emitted from an orbiting laser (step1). Then, debris
in the area reflects light whose portion enters into the laser gain material (step2). Then, four-wave mixing among the debris-reflected signal beam and light beams traveling between the two laser mirrors interfere each other. In the region of constructive interference, excited atoms in the gain material are dropped to the lower energy level, and then the gain is modulated according to the intensity pattern of the interference. The modulated gain acts as the gain gratings that diffract light (PCL) in the direction of the target debris (step3). If phase objects are in the optical light path, double-passing the phase object cancels wavefront distortions as shown in Fig. 2, allowing near-diffraction limited beam focusing on the small space debris. Because the response speed of the phase conjugator is much faster than the conventional mechanical steering method, the processes are done in real-time with no change in the setup, which enables tracking fast moving objects.

Fig. 1. Process of small space debris removal using PCL generated through saturable gain four-wave mixing in a laser resonator. Step1, target acquisition; step2, writing interference patterns by E1, E2 and the signal beam; step3, PCL generation through gain gratings. M, mirror; E1 and E2, forward and backward pumping beam; OC, optical coupler; DO, divergent optics.

When high energy density is achieved on the small space debris, laser ablation occurs that generates plasma plume. The momentum of the debris is then changed and the debris deviates from its stable orbit. Enough velocity change makes the debris re-enter the earth’s atmosphere before making one complete orbit. Figure 3 shows atmospheric re-entry trajectories for two cases when velocity change occurred in radially-outward and tangentially-decelerating directions. The results were obtained numerically by considering kinetic energy and balance between centrifugal force and gravity. The initial change velocity was decided so that the debris enters the earth’s atmosphere (200 km altitude) at the perigee. Although the laser-ablation plume is generated in the direction of surface normal and the direction of velocity change cannot be controlled easily, Fig. 3 shows that re-entry is possible even when the debris is forced out from the earth. After the re-entry, friction of the atmosphere burns up the debris.

Next, required PCL energy for deorbiting debris traveling in low-earth orbit (LEO) is estimated. Assuming dropping small space debris of one gram to the atmospheric at the altitude of 200 km, and the debris re-enter the atmosphere before making one complete orbit, PCL energy of several kilojoules is found to be needed as shown in Fig.4. Here, we supposed the momentum coupling coefficient $C_m$ is 100N/MW.

Fig. 2. Wavefront correction by PCL. Wavefront distortions can be canceled out and the original wavefront is reconstructed as the replica of the incident light (PCL) passes through the same phase object. PCM, phase conjugate mirror (phase conjugator).

Fig. 3. Atmospheric re-entry trajectories when velocity change occurred in radially-outward direction (left), and tangentially-decelerating direction (right).

Fig. 4. Estimated required PCL energy v.s. debris initial altitude.
3. Experimental setup and Results

Experimental setup is shown in Fig. 5. Four-wave mixing occurs in a 10-cm-long Nd:YAG crystal rod of 1 cm diameter in a Fabry–Perot resonator composed of a rear mirror and an optical coupler (partially reflecting mirror) of 40% reflectivity. The output beam size is reduced to 3.5 mm by two lenses so that signal and PCL can be observed by a beam profiler with imaging area of 6.5×4.8 mm. A beam splitter with 95% reflectivity is used as a target. The target-reflected laser output (signal beam) enters the rod with incident angle of one degree. Generated PCL travels back along the incident signal light path to the target. Part of the transmitted light at the target (beam profiler) is captured by the beam profiler. Two irises on the signal light path are used to ensure that generated PCL retraces its original light path. Figure 6 (a) and (b) show original signal beam and generated PCL. One can see that almost the same wavefront was reconstructed. Figure 6(c) shows generated PCL when half the signal beam was blocked by inserting a black paper between the optical coupler and the half-wave plate. When the half-wave plate is rotated so that the polarization direction of the transmitted signal beam becomes orthogonal to the forward and backward pump beams, no beam was observed as shown in Fig. (d) because orthogonally polarized beams do not interfere each other. The results indicate that PCL is truly generated through gain gratings and the time-reversal property was confirmed. The maximum PCL energy of 0.3 J was obtained.

Fig. 5. Experimental setup. E1, E2, forward and backward pump beam; M, mirror; O.C., optical coupler; BS, beam splitter.

Fig. 6. Beam profiles of (a) original signal beam, (b) generated PCL, (c) PCL when half the signal beam was blocked, and (d) output when signal beam is polarized orthogonal to the other beams by rotating the half-wave plate.

4. Discussions

As shown in Fig. 4, required PCL energy is several kilojoules. In order to achieve that high-energy, introducing a master oscillator power amplifier (MOPA) system is effective. By adding amplifiers, both weak target-reflected light and generated PCL can be amplified at a desired level. The efficiency of the system is determined largely by this amplifier system. Usually, light beams passing through amplifiers experience thermal lensing and other thermal effects such as thermal birefringence that degrade output beam quality. PCL, however, cancels out those effects and reconstructs its original wavefront. Therefore, high energy PCL can be generated maintaining the tracking performance determined by this PCL generation system.

5. Summary

Small space debris removal scheme using PCL was explained. Required PCL energy for deorbiting debris of one gram from LEO was estimated to be several kilojoules. Phase conjugator for removing the debris was developed and PCL generation was succeeded. The time-reversing property was confirmed by observing original signal light and generated PCL. Introducing MOPA system was proposed to be an effective way to increase PCL energy without losing beam quality.

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References

