Two-way wavelength conversion for visible and infrared signal pulses

M. Saito*, H. Kimura, S. Nakamura

Department of Electronics and Informatics, Ryukoku University, Seta, Otsu 520-2194, Japan

*Corresponding author: e-mail: msaito@rins.ryukoku.ac.jp

Abstract:

Two-way wavelength conversion was achieved for visible and infrared signal pulses by using a phosphorescent disk. When a visible (530 nm) or infrared (980 nm) laser beam was focused on the disk, absorbed photons created bright spots that emitted both visible and infrared phosphorescence (upconversion and downconversion). Although the phosphorescence lasted for 1 ms, a pulse signal of 1 MHz (1 μ s period) was detected successfully by circulating the bright spots on the disk (a time-space conversion method). In comparison with downconversion, upconversion was easier to achieve for high-frequency signals, since the two-photon absorption process prevented overlapping of adjacent spots by restricting the phosphorescence spot size.

Highlights:

Two-way wavelength conversion was achieved for visible and infrared optical pulses.

A single all-optical device realized both upconversion and downconversion.

A time-space conversion method was used to create short pulses from phosphorescence.

Pulse signals of 1 MHz were converted successfully by rotating a phosphorescent disk.

Keywords:

Upconversion; Phosphorescence; Time-space conversion; Two-way device; All-optical device

1. Introduction

Rare earth elements play an important role in many optical devices, e.g., solid-state and fiber lasers [1], fiber amplifiers [2], color displays and white illuminators (lamps, LEDs) [3], afterglow phosphors [4], etc. Advances in optical technology are still accelerating the needs for these elements in spite of their rarity. The needs for rare earth elements usually come from the fact that their excited states have a long lifetime (sub-millisecond or longer) [5]; e.g., a population inversion has to be attained in lasers and amplifiers, and a long-lasting phosphorescence is required in displays and glow-in-the-dark illuminators. Thermal and photochemical durabilities are also their advantages, since reliable performance and maintenance-free operation are of particular importance in communication devices and illuminators. These characteristics contrast with organic dyes, which generally possess a short excitation lifetime (nanoseconds or shorter) and readily degrade by photobleaching or thermal dissolution [6].

A two-way wavelength conversion is a distinctive function that is attainable with rare earth doped phosphors but unattainable with other dyes. According to the law of energy conservation, decreasing a photon energy (downconversion) is readily achievable, but increasing a photon energy (upconversion) needs a complicated process. Upconversion is usually induced by combination of multiple coherent photons, and hence, requires ultra-short pulses or a phase-matching process, e.g., a quantum-mechanical two-photon absorption or a harmonic generation. The long lifetime of rare earth elements, however, realizes an upconversion process that requires no complicated optical systems [7]. That is, an electron is excited to an intermediate state by absorbing a photon, and stays at that state for a while (during a lifetime of that state) waiting for another photon arrival. Then the electron is excited to a higher energy level by absorbing a second photon and emits a high energy photon.

Since the early days of the upconversion research [8], a variety of phosphors have been

developed by doping rare earth elements in crystals (powders) [9– 11], glass ceramics [12], glasses [13, 14], or glass fibers (waveguides) [15, 16]. Most phosphors emit green or red light, and some emit violet [17] or white (red-green-blue, RGB) light [18– 20]. Research interests are currently directed to enhancement of the phosphorescence efficiency or brightness, e.g., fabrication of nano-sized particles [21– 23] or surface-plasmonic enhancement of phosphorescence [24, 25]. By using these upconversion phosphors, researchers have developed various optical devices [26– 29] including 3-D displays [30, 31]. In recent years, applications to biotechnology have been studied extensively [32– 35].

In this study, we used an upconversion phosphor to construct a two-way wavelength converter. Optical communication systems are currently operated in various spectral ranges, e.g., the 1300– 1600 nm band for the long-haul transmission systems, the 800– 1000 nm band for the wire-less networks, the red band for the polymer-based interconnections, and the entire visible band (white light) for the mobile communication systems based on LED illuminators. All-optical wavelength conversion is desired to interconnect these different communication systems. As a first step to achieving the two-way conversion, we conducted experiments by using Yb^{3+} - Er^{3+} co-doped $\text{Gd}_2\text{O}_2\text{S}$ powder (Phosphor Technology, PTIR545/F). Figure 1 shows the emission processes of this phosphor [5]. Er^{3+} is responsible for emission, and Yb^{3+} facilitates the two-photon absorption because of its high infrared absorbance [8, 9]. In the upconversion process, infrared photons in the 1000 ± 80 nm range are absorbed, and phosphorescence occurs in the 540 ± 10 nm range (green). In the downconversion process, green light excites electrons and induces infrared emission.

As mentioned earlier, a long lifetime of the excitation states is essential for achieving an efficient wavelength conversion. The long lifetime inevitably causes afterglow with a long decay time, which is preferred for uses in nonelectric illuminators [4, 36], imagers [37] and tracers [38]. As regards the wavelength conversion, however, the long lifetime is unfavorable

since it restricts the signal frequency or bit-rate; i.e., the afterglow causes an overlap of successive pulses. When the pulse frequency of an excitation signal exceeds 1 kHz (1 kbit/s), for example, phosphorescence becomes continuous and carries no trace of signal pulses. In a previous paper [39], we proposed a time-space conversion method to realize a fast-response upconversion. In this method, optical pulses are irradiated on a disk containing the phosphor, as shown in Fig. 2(a), and create a bright spot array as the disk rotates. By picking up phosphorescence from these spots, signal pulses can be reproduced regardless of the afterglow time. A pulse signal upconversion from 940 to 530 nm was demonstrated successfully in the previous experiment. In the current experiment, we examine the validity of this method in the downconversion process to demonstrate the feasibility of the two-way conversion. We also examine whether a pulse signal of 980 nm can induce an efficient upconversion, since this wavelength is more suitable than 940 nm for matching the input and output signal wavelengths.

2. Optical system

Figure 2(a) shows the optical system that was constructed for the two-way wavelength conversion. The signal source was a laser diode of 980 nm (output power: 900 mW) or a frequency-doubled Nd:YAG laser of 530 nm (300 mW). The laser beam was modulated by using an acousto-optic modulator to generate a pulse signal of 1–3000 kHz. Figure 2(b) shows a 980 nm signal that was measured at the exit end of the input fiber (a silica glass fiber of 200 μm diameter). As the arrow shows, the detector signal varied between 40 and 400 (arbitrary unit), and hence, the modulation factor was $(400-40)/(400+40)=82\%$ at this frequency. The average optical power was 260 mW. Figure 2(c) shows the maximum and minimum of the signal intensity that were measured at various modulation frequencies. Although the average signal power was unchanged, the modulation factor decreased notably beyond 1 MHz because

of the operation limit of the acousto-optic modulator. This input beam was imaged on the phosphor disk (1:1 magnification) by using a lens. The upconversion phosphorescence of the disk was picked up with another couple of lens and optical fiber, which were placed symmetrically with the input optical system. When the downconversion experiment was conducted with the 530 nm light, the ends of the two fibers were changed with one another, as shown by dashed lines in Fig. 2(a). Consequently, the signal beam progressed reversely in the two lens systems (two-way transmission). The modulated 530 nm light exhibited a similar signal shape and a similar frequency characteristic as those shown in Figs. 2(b) and 2(c). The average signal power was 50 mW.

The phosphor disk consisted of two polycarbonate disks (120 mm diameter) that sandwiched the phosphor powder [39]. As Fig. 2(a) shows, the input light created a series of phosphorescent spots on the disk that rotated at 40 revolution/s. In a previous experiment, we observed a delay signal by picking up the phosphorescence at a downstream position of the spot flow [39]. In the current experiment, however, the output signal (phosphorescence) was picked up at the irradiation point of the input signal, since the input and output optical systems had to be equivalent in the two-way transmission device.

A gray line in Fig. 3(a) shows an upconversion signal spectrum that was measured at the exit end of the output fiber. A pronounced peak at 980 nm was attributed to the input light that was scattered at the disk surface. Broad phosphorescence peaks are visible in the wavelength ranges of 530– 550, 650– 680, 800– 860, and 920– 1080 nm, which correspond to electronic transitions between several different energy levels [5]. To extract a green signal from this phosphorescence, a color filter was inserted in front of the output fiber, as shown in Fig. 2(a). As the black line in Fig. 3(a) shows, this filter was opaque in the 600– 1100 nm wavelength range, and hence, removed the unwanted noise light, i.e., the scattered input light and the phosphorescence at the other wavelengths.

1 In the downconversion experiment, the input and output fibers were connected to the
2 opposite side of the converter, as shown by dashed lines in Fig. 2(a). A modulated green laser
3 beam was delivered by the input fiber and irradiated the phosphor disk from the lower side.
4 The color filter did not hinder this signal transmission, since it was transparent in the green
5 spectral range. The gray line in Fig. 3(b) shows a phosphorescence spectrum that was
6 measured through the output fiber on the other side of the converter. The spectrum was similar
7 to that in Fig. 3(a) except that a peak of the scattered input light appeared at 530 nm. To
8 eliminate unwanted spectral lines, another color filter was inserted in the optical path (the
9 upper side of the converter). As the black line in Fig. 3(b) shows, this filter possessed a
10 band-pass transmission characteristic for the 900– 1020 nm wavelength range. Insertion of this
11 filter caused no problem to the other input signal (980 nm), since it was transmissive at the
12 signal wavelength.

13 Figures 3(c) and 3(d) show the input and output signal spectra in the upconversion and
14 downconversion processes. As mentioned earlier, the signal upconversion capability was
15 demonstrated by using a 940 nm laser diode in the previous experiment [39]. In the
16 downconversion process, however, phosphorescence was stronger at 980 nm than 940 nm, as
17 shown in Fig. 3(b). A 980 nm laser was therefore used as an input signal source in the current
18 experiment. As Figs. 3(c) and 3(d) show, the input and output signal wavelengths were
19 reversed successfully in the current two-way conversion process.

20 **3. Experiment and discussion**

21 Figures 4(a)– 4(c) show the upconversion signals that were measured by a photodetector at
22 the output fiber end. These signals oscillated up and down across 0 V, since the detector output
23 was AC-coupled for signal amplification. When the modulation frequency of the input infrared
24 signal was 20 or 50 kHz, a clear output signal was detected. The output signal intensity

decreased gradually as the frequency increased, and the pulse signal became undetectable beyond 200 kHz. Note that the input signal had a sufficient modulation factor ($>80\%$) below 1 MHz, as shown in Fig. 2(c). The signal pulses were therefore assumed to have disappeared in the wavelength conversion process.

Let us consider what determined the frequency limit of the wavelength conversion. In the current experiment, the rotation rate of the phosphor disk (120 mm diameter) is 40 revolution/s, and the bright spots draw a circular trajectory of 110 mm diameter. The linear velocity of the spots is therefore 14 m/s. If the input signal frequency is f , the distance between two adjacent spots is $14/f$. At 200 kHz (the detection limit), for example, the distance between spot centers is evaluated to be 70 μm . The bright spot diameter is therefore assumed to be smaller than $\sim 70 \mu\text{m}$, since otherwise bright spots overlap one another creating a continuous phosphorescence signal (no modulation). This assumed spot size is smaller than the image size of the fiber end (200 μm diameter) or the input beam diameter. Probably the upconversion phosphorescence is emitted only at the beam center, since the two-photon absorption is difficult to take place at the outer region where the photon density (the input light intensity) is low.

Next, the input signal of 530 nm was transmitted in the reverse direction to generate a downconversion signal. Figure 4(d) shows the output signal that was detected at 20 kHz. As Fig. 4(e) shows, however, the signal became undetectable at 50 kHz. When the detector signal was measured by DC-coupling, a flat signal with no modulation appeared, as shown in Fig. 4(f). This result indicated that the pulse signal vanished not because the phosphorescence (the output signal) was weak but because the bright spots overlapped one another.

Although the 200 kHz signal is detectable in the upconversion process, the modulation frequency is limited below 50 kHz in the downconversion process. This fact is related to the excitation mechanism of the phosphor. As mentioned earlier, the upconversion

phosphorescence is restricted to a narrow region in which two-photon absorption takes place.

By contrast, the downconversion phosphorescence takes place in the entire region to which the input beam is collected. In addition, the powdery phosphor heavily scatters the input light and expands the input beam diameter (200 μm). The spot distance is evaluated to be 280 μm , when the modulation frequency is 50 kHz and the rotation rate is 40 revolution/s. The diameter of the bright spots probably exceeds this spot distance in the downconversion process.

The consideration above suggested that the modulation frequency could be raised by either increasing the disk rotation rate or decreasing the input beam diameter. When the rotation rate was raised to 80 revolution/s, however, no stable signal was attainable, since the disk vibrated heavily as the rotation rate increased. To reduce the input beam diameter, we removed the optical fibers and irradiated the modulated laser beam directly to the phosphor disk. The focused beam diameter was 20–30 μm on the disk surface.

Figure 5(a) shows an upconversion signal that was detected by irradiating a 980 nm signal directly to the phosphor disk. A clear sinusoidal signal was visible at 1 MHz. The bright spot distance was evaluated to be 14 μm at this modulation frequency, since the disk rotated at 40 revolution/s. It was assumed that only the central portion of the input beam induced the two-photon absorption and the green phosphorescence.

Figure 5(b) shows a downconversion signal that was measured by focusing a 530 nm beam on the phosphor disk. Although a signal of 1 MHz was detectable, its shape was heavily distorted. This result also indicated that a superior performance was attainable in the upconversion process than the downconversion process.

A reason for the spot expansion is the scattering by the phosphor powder (average size: 3 μm). If a transparent upconversion glass is used [40], the modulation frequency can be raised in the downconversion process. The increase of the disk rotation rate is also effective to improve the frequency characteristic. The current disk that was made by adhering two DVD

1 disks vibrated heavily during the high-speed rotation process because of a poor mechanical
2 balance. Recent technology has developed polygonal mirrors that are driven by an electric
3 motor with a rotation rate exceeding 600 revolution/s [41]. We are currently trying to use this
4 technique in our phosphor disk. Also, this polygonal mirror technique is usable in another
5 way; i.e., the time-space conversion is achievable by scanning a signal beam on a fixed
6 phosphor plate instead of rotating the phosphor disk. This configuration seems more suitable
7 for creating a compact optical device.
8

9 In solid state lasers and fiber amplifiers, short pulses are generated or amplified by using
10 rare earth elements. The long lifetime does not matter in these devices, since stimulated
11 emission generates a strong pulse that overcomes the afterglow effect. If stimulated emission
12 is induced by placing a phosphor in a resonator, a fast wavelength conversion may be
13 achievable without the use of rotation mechanism.
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16 **4. Conclusion**

17 Two-way wavelength conversion was conducted by using a rare earth doped phosphor. To
18 eliminate the afterglow effect that prevented the fast response, a pulse signal in the time
19 domain was converted to a phosphorescent spot array in the space domain. Signal pulses of
20 530 and 980 nm wavelengths were converted to one another at 1 MHz modulation frequency.
21 The time-space conversion method will be useful to interconnect optical networks that are
22 operated at various wavelengths.
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Figure captions

Fig. 1. Energy levels of an Yb^{3+} - Er^{3+} co-doped phosphor. Numerals beside the arrows denote the absorption or emission wavelengths that correspond to the electronic transition.

Fig. 2. (a) Optical system for conducting the two-way wavelength conversion of signal pulses. (b) Input signal shape that was measured at the input fiber end. The original continuous-wave (CW) laser beam was modulated at 10 kHz by using an acousto-optic modulator. (c) Modulation efficiency of the input signal. The open and closed circles show the maximum and minimum values of the input signal. The arrow corresponds to that in (b).

Fig. 3. (a) Upconversion or (b) downconversion phosphorescence spectrum (gray line) that was measured at the output fiber end with no color filter. The black line shows the transmission spectrum of the color filter that was placed in front of the output fiber. A pronounced peak at (a) 980 or (b) 530 nm wavelength originated from the scattered input signal (excitation light). (c, d) Signal light spectra that were measured at the input and output fiber ends. The output light spectrum was measured through the color filter shown in (a) or (b).

Fig. 4. Output signals in the (a– c) upconversion and (d– f) downconversion processes. Input signal frequencies are shown in the figures. The detector signal was AC-coupled to the oscilloscope except for the background noise in (f) that was monitored by DC-coupling.

Fig. 5. Output signals that were measured by removing both the input and output fibers. The input signal frequency was 1 MHz. (a) shows an upconversion signal that was detected through the color filter shown in Fig. 3(a). (b) shows a downconversion signal that was detected through the color filter shown in Fig. 3(b).

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