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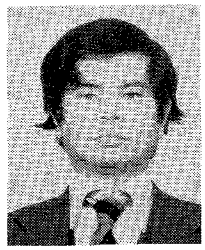

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Two-Wave Sum-Frequency Light Generation in Optical Fibers

YASUJI OHMORI AND YUTAKA SASAKI

Abstract—**The generation of phase-matched two-wave sum-frequency light has been observed in optical fibers. A Nd:YAG laser by simultaneous mode-locking and Q-switching or only Q-switching operation is used as a pump laser. The input power dependence and fiber length dependence of the sum-frequency light are investigated in the two pumping methods. The observed coherence length for the sum-frequency light generation is about 200 m.**

I. Introduction

LOW-LOSS optical fibers have proven to be highly suitable media for the observation of a wide variety of optical nonlinear effects, such as stimulated Raman scattering [1]-[4], stimulated Brillouin scattering [5], [6], self-phase modulation [7], and phase-matched four-photon mixing [8], [9]. The reason has to do with high optical intensities maintained over long lengths in small-core and low-loss fibers.

Low-loss optical fibers have come to be applied to active elements for generating new laser wavelengths [10]-[12] by using stimulated Raman scattering and phase-matched four-photon mixing processes. The generation of a near-infrared continuum covering the 0.7-2.1 μm range by use of a Q-switched Nd:YAG laser with 50 kW pump power coupled into multimode fibers has been observed previously [11]. In that work, transitory observations of visible-light generation were made. Recently, the wideband spectrum covering the 0.3-2.1 μm range was observed by using a mode-locked and Q-switched Nd:YAG laser with more than 100 kW pump power coupled into multimode fibers [13]. In this work, the generation of sum-frequencies was observed in cladding modes of silicone plastic coated fibers with 5-15 m lengths and a 50 μm core diameter.

In a previous letter [14], the authors reported the first observation of phase-matched two-wave sum-frequency light generation achieved by using waveguide modes of optical fibers. The mechanism of sum-frequency light generation, however, has not been readily explainable because the two-order dipole nonlinear coefficient for silica-based fibers has been thought to be zero. It is, therefore, very interesting to investigate how the sum-frequency light generation depends on pumping light, fiber length, or exciting condition.

This paper describes characteristics of sum-frequency light generation in optical fibers. The two-wave sum-frequency light waves were generated from the pump and the Stokes waves in optical fibers, pumped by a mode-locked and Q-switched Nd:YAG laser or a Q-switched Nd:YAG laser. The input power dependence and fiber length dependence of the output power of 0.54 μm light, which is generated from a combination of the pump light of 1.064 μm and the first Stokes light of 1.12 μm, were investigated in the two pumping methods. The sum-frequency light generation was also investigated in optical fibers in which the two modes (LP_{01} and LP_{11}) were excited. In this exciting condition, 0.53 μm light which is the second harmonics of 1.064 μm pump light, was newly observed.

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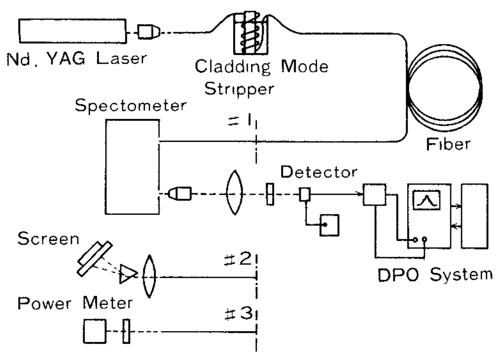

Fig. 1. Experimental arrangement for the observation of two-wave sum-frequency light generation.

II. Experimental Procedures

The experimental arrangement is shown in Fig. 1. A Nd:YAG laser utilizing mode-locking and Q-switching or the Q-switching operation alone was used as a pump laser. The Nd:YAG laser was operated at 1.064 μm in a single transverse mode. The Q-switched pulses were a train of about 1 μs pulses with 2 ms pulse spacing. The mode-locked pulses were a train of about 500 ps pulses with 10 ns pulse spacing. The peak power by simultaneous Q-switching and mode-locking was more than 14 kW and that by only Q-switching, 1 kW. The optical fiber prepared for this experiment was fabricated by a vapor-phase axial deposition method, namely, the VAD method [15], and was a two-mode-number fiber. The fiber parameters are shown in Table I.

The pump light was directly coupled into the optical fiber with a 20X microscope objective. Several turns of the fiber near the input end were wound on a 3 cm radius cylinder and were immersed in liquid to remove any undesired excited cladding modes and excite mainly the fundamental mode (LP_{01}). The fiber output end was carefully set with a microscope for accurate detection. The output light emerging from the fiber end was examined in three ways (#1, #2, and #3) as shown in Fig. 1. The light was passed through the spectrometer, collimated by a 20X microscope objective and a lens (f = 5 cm), and detected by a Si-APD (avalanche photodiode) or a Ge-APD. Since the Ge detector is relatively insensitive to green, the Si detector was used to measure visible light. The spectrum in more than 1.05 μm was measured through a filter, which absorbs visible light. The detected pulse shapes of the output light were recorded after being integrated and averaged with a Tektronix digital processing oscilloscope system (DPO system; WP-1200) (#1 in Fig. 1). The mode-patterns of the output light were projected on a photographic screen after they were dispersed through a prism (#2). The average power of the output pulses was detected by a pyroelectric powermeter (Molectron, PR-200) through a filter (#3). The peak power of the input pulse was determined from the average power and the pulse shape, which was measured for a 2 m long fiber.

The peak pump power coupled into the fiber input end, that is, the input power was varied by changing the pump laser output power. The fiber output end was carefully set at the same position on the fiber holder by using a microscope for accurate output power detection through a spectrometer.

TABLE I
Fiber Parameters

Core Composition	$SiO_2 - GeO_2$
Core Diameter	6.1 µm
Cladding Composition	SiO_2
Cladding Diameter	125 µm
Relative Refractive Index Difference	0.59 %
Cutoff Wavelength	1.27 µm
Transmission Loss	1.30 dB/km (at 1.064 µm)

III. Experimental Results

A. Sum-Frequency Light Generation Utilizing Q-Switching and Mode-Locking Operation

1) Input Power Dependence: The spectra, which were generated in the 270 m long fiber at a peak input power of 2.7 kW, were reported [14]. The spectra show the generation of two-wave sum-frequency waves which have two peak wavelengths of 0.54 and 0.56 μm, of the anti-Stokes from 0.7 to 1.04 μm, and of the Stokes from 1.1 to 1.7 μm.

Fig. 2 shows the input power dependence of the 0.54 μm sum-frequency output power by mode-locking and Q-switching. The generation of two-wave sum-frequency light generation was observed above 0.8 kW and found to increase in proportion to the square root of the input power.

2) Fiber Length Dependence: Fig. 3 shows the fiber length dependence of the 0.54 μm output power by mode-locking and Q-switching with 7 kW of input power. The sum-frequency light was observed above 4 m. The 0.54 μm output power increases almost exponentially with increases in fiber length from 4 to 17 m. It becomes nearly constant above 17 m because the group velocity dispersion causes walk-off between the pump wave, the Stokes waves, and the sum-frequency waves for short pulses in long fibers. This group velocity mismatching limits the interaction fiber length in which the pulses of the three waves interact with each other effectively. Fig. 3 shows that the interaction fiber length for the sum-frequency light generation by mode-locking and Q-switching is about 17 m and is shorter than the coherent length for the sum-frequency light generation.

B. Sum-Frequency Light Generation Utilizing Q-Switching Operation

1) Input Power Dependence: Figs. 4 and 5 show the spectra of the output light emerging from a 100 m long fiber, pumped by only a Q-switched Nd:YAG laser with 75 and 150 W peak input powers, respectively. Sum-frequency light waves

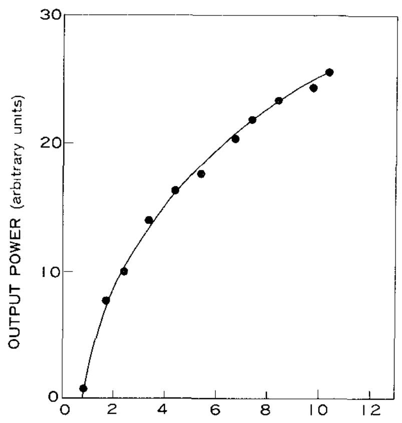

Fig. 2. Output power for 0.54 μm sum-frequency light versus input power. A mode-locked and Q-switched Nd:YAG laser is used as a pumping laser. Fiber length is 270 m.

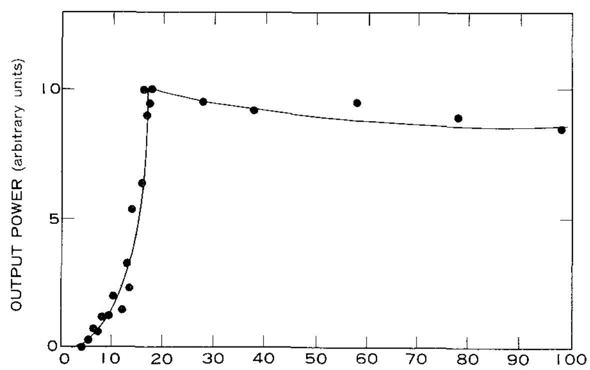

Fig. 3. Output power for 0.54 μm sum-frequency light versus fiber length. A mode-locked and Q-switched Nd:YAG laser is used as a pumping laser. Input power is 7 kW.

were not generated at 75 W input power, as seen from Fig. 4, and were observed above 80 W input power. It can be seen from Figs. 4 and 5 that the continuum of the Stokes covering the 1.24–1.5 μm range at 75 W input power are generated more strongly than that at 150 W input power. As the input power increases above 75 W, the output power peak wavelength shifts to longer wavelength region covering above 1.5 μm. Since the Ge avalanche photodiode is relatively insensitive at more than a 1.6 μm wavelength, the output power in Figs. 4 and 5 decreases rapidly at more than a 1.6 μm wavelength.

Fig. 6 shows the dependence of the output power on the input power for the 0.54 μm sum-frequency light generated by the Q-switching. The dependence of the pump and the first Stokes waves are also shown in Fig. 6. The input power and the output power were measured at the center of the Q-switching pulse shape. The sum-frequency light was observed above 80 W and found to increase with the square of the input power. The output powers of the pump and the first Stokes decreased exponentially between the input power of 45 and 80 W, and were constant above 80 W.

2) Fiber Length Dependence: Fig. 7 shows the fiber length dependence of the 0.54 μm output power from the Q-switching with 160 W input power. The sum-frequency light

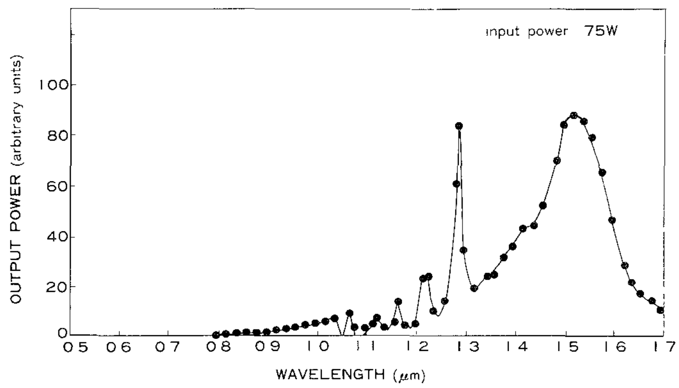

Fig. 4. Spectra for output light emerging from a 100 m long fiber, pumped by a Q-switched Nd:YAG laser at 75 W peak input power.

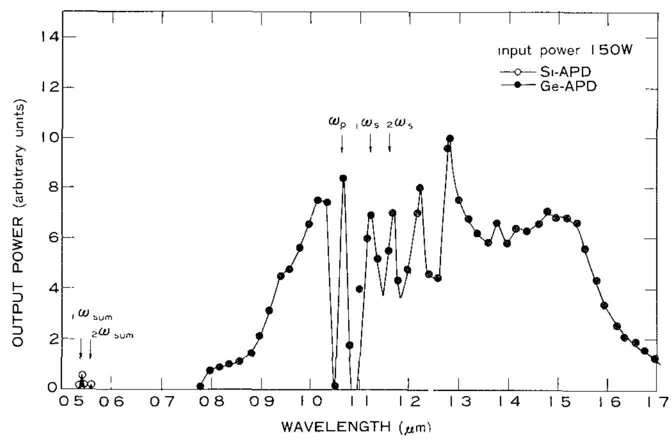

Fig. 5. Spectra for output light emerging from a 100 m long fiber, pumped by a Q-switched Nd:YAG laser at 150 W peak input power:

$_1\omega_{sum} = \omega_p + {_1\omega_s}$: 0.54 μm light
$_2\omega_{sum} = \omega_p + {_2\omega_s}$: 0.56 μm light
ω_p: pump light
$_1\omega_s$: 1st Stokes light
$_2\omega_s$: 2nd Stokes light

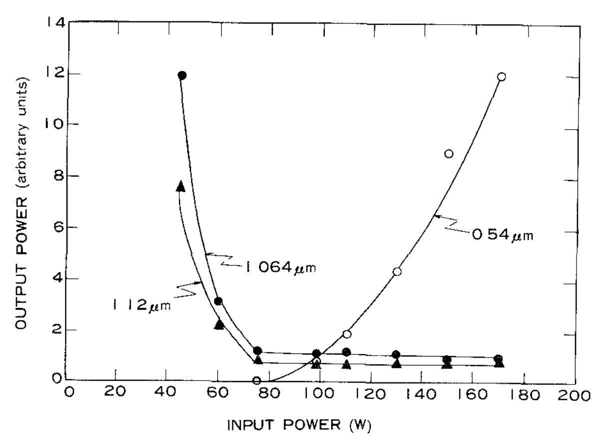

Fig. 6. Output powers for 0.54 μm sum-frequency light, 1.064 μm pump light, and 1.12 μm first Stokes light versus input power. A Q-switched Nd:YAG laser is used as a pumping laser. Fiber length is 100 m.

was observed above 10 m. The 0.54 μm light increases almost along a cosine curve with increases in the fiber length from 10 to 200 m, and becomes nearly constant above 200 m. This result shows that the coherence length for sum-frequency

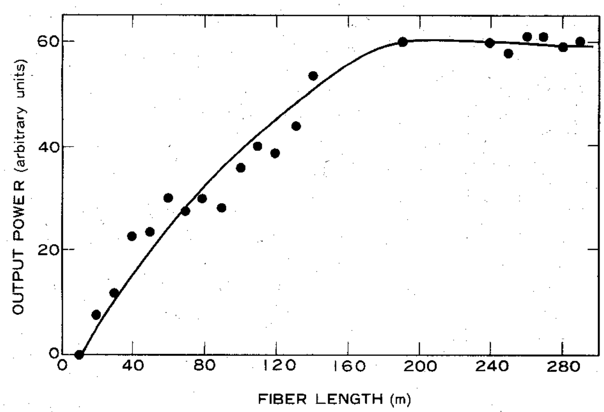

Fig. 7. Output power for 0.54 μm sum-frequency light versus fiber length. A Q-switched Nd:YAG laser is used as a pumping laser. Input power is 160 W.

light generation by Q-switching is about 200 m long. The interaction fiber length for the three waves, after being described, is about 2.5 km.

C. Sum-Frequency Light Generation at LP_{01} and LP_{11} Modes Exciting Condition

In order to excite LP_{01} and LP_{11} modes into fibers, the experiment was done without the cladding mode stripper in Fig. 1. The mode patterns of the generated visible output light were obtained, as shown in Fig. 8. This figure shows the higher order mode of second harmonics, whose output power comprised about one part in 10^4 of the total of output light. The conversion efficiencies of 1.1×10^{-3} and 0.5×10^{-3} from the pump wave into the two sum-frequency waves of 0.54 and 0.56 μm, respectively, were also obtained.

IV. Discussion

Using the law of energy conservation, the green waves were identified as the two-wave sum-frequency waves, which were generated from the combinations of the 1.064 μm pump wave and the Stokes waves. Phase matching requirement is $\beta_p + \beta_s = \beta_{sum}$, where β_p, β_s, and β_{sum} are the propagation constants for the pump wave, the Stokes wave, and the sum-frequency wave, respectively. The propagation constant for LP_{1m} mode, where 1 is zero or an integer and m is an integer, was obtained from characteristic equation [16], using the refractive index of GeO_2-SiO_2 glass [17]. The calculated propagation constants are shown in Table II. The calculation indicated that the sum of β_p at 1.064 μm for LP_{01} mode and β_s at 1.12 μm for LP_{01} mode was nearly equal to β_{sum} at 0.54 μm for LP_{02} or LP_{21} mode, and the sum of β_p at 1.064 μm for LP_{01} mode and β_s at 1.18 μm for LP_{01} mode was nearly equal to β_{sum} at 0.56 μm for LP_{21} mode.

The differences between the characteristics of the sum-frequency light generated by simultaneous mode-locking and Q-switching and only Q-switching are due to the interaction fiber length in which the three waves interact with each other effectively. The transit time delay difference between the pulse at 1.064 μm and that at 0.54 μm can be estimated to be 63 ps/m. The complete separation of the pump and the sum-frequency light pulses due to group velocity dispersion occurs at about 8 m for mode-locked and Q-switched laser pumping because the pulses have about a 500 ps half width. The interaction fiber length for Q-switched laser pumping occurs at more than 2.5 km fiber length. Therefore, the coherence length for the sum-frequency light generation is determined accurately with Q-switching operation. Fig. 7 shows that the coherence length for the sum-frequency light generation by Q-switching is about 200 m long.

Most of the nonlinear processes observed in optical fibers, such as the stimulated Raman scattering and the stimulated Brillouin scattering, are based on the third-order dipole nonlinear coefficients in the polarization expansion. The non-

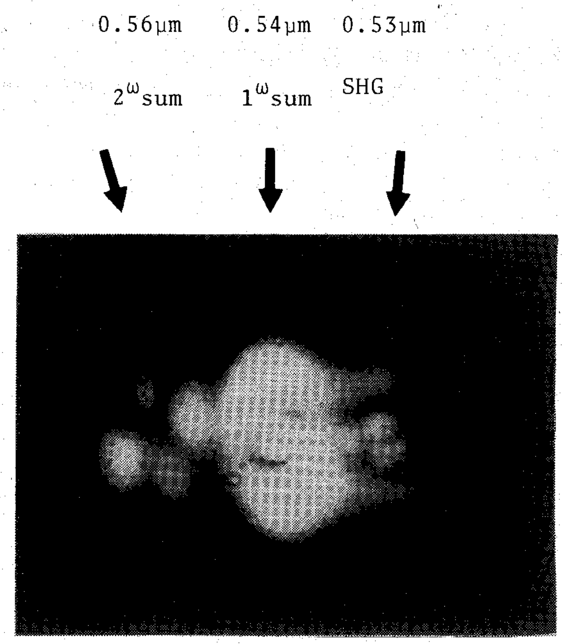

Fig. 8. Photograph of the far-field mode patterns of output light emerging from the fiber end after being dispersed through a prism. The experiment was done without the cladding mode stripper in Fig. 1.

TABLE II
PROPAGATION CONSTANTS

Wavelength	Propagation Constant $\times 10^6$ (m^{-1})		
	LP_{01}	LP_{02}	LP_{21}
1.18 μm	7.7894	——	——
1.12 μm	8.2092	——	——
1.064 μm	8.6360	——	——
0.56 μm	16.5151	16.3143	16.3219
0.54 μm	17.1361	16.9361	16.9437

linearity-producing two-wave sum-frequency generation in silica-based fibers could be originated by a quadrupole nonlinearity and/or a dipole nonlinearity. The experiments are summarized as follows.

1) Figs. 4 and 5 show that the sum-frequency light generation is observed above the input power at which four-photon process occurs.

2) Fig. 7 shows that the coherence length for sum-frequency light generation is very long.

3) Fig. 8 shows that conversion efficiency of the second harmonics is less than that of two-wave sum-frequency wave.

These experimental results imply that the origin of nonlinearity-producing sum-frequency light generation is quadrupole moment. Further investigation is, however, necessary to determine whether the origin of the two-wave sum-frequency light generation may be attributed to the quadrupole moment or the dipole moment.

V. Conclusion

This paper has reported phase-matched two-wave sum-frequency light generation of the green wave from the 1.064 μm pump and the Raman Stokes waves in optical fibers. Phase matching was achieved by using the waveguide mode dispersion of the silica-based fibers to compensate for bulk dispersion. The observed coherence length for the two-wave sum-frequency light generation is about 200 m. The present results imply that the origin of the nonlinearity-producing sum-frequency light generation is a quadrupole moment. Further investigation, which includes experimental and theoretical studies for the interaction fiber length and the depletion effects of the pump and the first Stokes light, is necessary to determine whether the origin may be attributed to a quadrupole or a dipole moment.

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Yutaka Sasaki, for a photograph and biography, see *IEEE J. Quantum Electron.*, p. 503.