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Generation of a wide discrete visible spectrum in a frequency-doubling optical fiber

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Abstract. We describe some special features of frequency doubling in a Ge-doped SiO_2 optical fiber. The generation of a multi-frequency visible spectrum in a single short fiber pumped with 1.06 μm radiation is demonstrated. This effect is the result of an interplay between the processes of frequency doubling and third-order nonlinear frequency mixing. Most of the new components coincide with the characteristic stimulated four-wave-mixing spectrum of the fiber, although the power of the internally generated 0.532 μm pump was more than an order of magnitude below the respective thresholds.

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Although most of the third-order nonlinear effects in optical fibers are adequately understood now [1], some new interesting phenomena can be observed when several processes occur simultaneously. In two earlier papers we have studied stimulated four-wave mixing (SFWM) and stimulated Raman scattering (SRS) under the influence of an additional pump wave with substantially different frequency. With such an additional pump we have obtained a remarkable reduction of the thresholds of these processes [2]. Moreover, we have generated in the field of both pump waves several distinct new frequency components, which have frequency shifts typical for the standard SFWM and SRS processes, associated with the other pump wave [3]. These effects are explained as originating from additional three-wave-mixing (TWM) processes, involving the two pump waves and their Stokes or anti-Stokes components.

Another interesting nonlinear phenomenon, which has recently been the object of extensive studies, is second-harmonic (SH) generation in optical fibers [4–6]. Although characterized with negligible conversion coefficients ($\approx 10^{-6}$), sum-frequency mixing based on $\chi^{(2)}$ nonlinearity in optical fibers has also been experimentally demonstrated [7].

The experimental results on SH generation in fibers indicate that the process has a relatively short coherence length, which usually does not exceed 10^{-1} m. On the contrary, because of the possibility of achieving exact phase synchronism, the length of the effective energy conversion for the SFWM processes is often comparable with the length of the fiber.

Hence, it seems possible to use the SH, generated in the short (5–10 cm) initial section of the fiber, as a pump wave for a parametric process in the next part of the fiber. As the results of [2] indicate, the threshold of this parametric process can be substantially reduced by the high power fundamental harmonic (FH). The realization of such an interaction would allow one to obtain a rich discrete spectrum in the visible range from a fiber, pumped with a single IR pump wave, thus increasing the capabilities of optical fibers as efficient frequency converters.

The feasibility of this idea was tested on the experimental setup described in [2]. The pumping source was a mode-locked CW Nd–YAG laser with Q-modulation. The mode-locking frequency was 100 MHz, and the frequency of Q-modulation was 700 Hz. The FWHM durations of the train and of the single pulses were 300 ns and 200 ps, respectively.

In this experiment we used a 1.5 m long fiber sample with a pure SiO_2 cladding and a core doped with 18 mol% GeO_2 ($\Delta n = 0.026$). The diameter of the core was 3.1 μm. At $\lambda_1 = 1.064$ μm this type of fiber supported two waveguide modes, while at $\lambda_2 = 0.532$ μm it supported four modes.

The characteristic SFWM spectra of the fiber were measured at pump wavelengths $\lambda_1 = 1.064$ μm and $\lambda_2 = 0.532$ μm before its preparation for an efficient SH generation. When pumped at $\lambda_1 = 1.064$ μm the fiber sustained a pair of parametric frequencies, shifted with $\Delta\nu = \pm 1210$ cm^{-1} from the pump. Several pairs of parametric frequencies, resulting from the different mode combinations, were obtained with pump wavelength $\lambda_2 = 0.532$ μm. The frequency shifts of the lowest threshold pairs were approximately 200, 420 and 640 cm^{-1}, respectively. For both $\lambda_1 = 1.064$ μm and $\lambda_2 = 0.532$ μm the standard SRS bands ($\Delta\nu_r \approx 440$ cm^{-1}) were observed in the output spectra as well.

For the preparation of the $\chi^{(2)}$ gratings, we applied the standard procedure with only a minor modification. During the recording phase (approximately 15 min), the external SH wave was gradually decreased, until it was comparable to the generated SH wave. The best results were obtained when the initial value of the external SH power was $P_2 = 0.3$ mW (peak power in the center of the laser train 125 W), which was lower than, but comparable to, the SFWM threshold. This recording technique allows the rapid production of gratings with frequency-doubling efficiencies that can reach 0.5–1% [6, 7].

After the preparation period, the external SH beam was blocked and the generation of new frequency components in the visible range around 0.532 nm was studied vs input FH power.

In our case, with an average FH pump power $\mathbf{P}_1 = 5$ mW (peak power 7 kW), we could not excite any nonlinear frequency conversion processes in the IR. With this pump power, the output spectrum in the visible range contained only the usual peak of the internally generated SH wave.

By increasing the FH pump power to $\mathbf{P}_1 = 7$ mW (peak power 10 kW) we observed in the IR only the first SRS Stokes component, as shown in Fig. 1a (denoted by $R^{(1)}$). The corresponding spectrum in the visible is shown in Fig. 1b, where the generation of several new frequencies is seen. These are respectively the internal SH ($\lambda_{shg} = 532$ nm) and three pairs of Stokes and anti-Stokes frequencies with frequency displacements from the SH of 200 cm^{-1} (denoted by $AS_1^{(2)}$ and $S_1^{(2)}$), 420 cm^{-1} ($AS_2^{(2)}$ and $S_2^{(2)}$), 640 cm^{-1} ($AS_3^{(2)}$ and $S_3^{(2)}$). The same parametric pairs, characteristic for the specific fiber sample, could also be simultaneously excited, with a variable relative efficiency, by the external SH pump.

An increase of FH pump power to $\mathbf{P}_1 = 10$ mW (peak power 14 kW) yields, along with the growth of the SRS band, a growth in the IR of the SFWM process. This gives rise to two new waves with frequency shifts $\Delta\nu \approx \pm 1210$ cm^{-1} (in Fig. 2a denoted by $AS_1^{(1)}$ and $S_1^{(1)}$). The corresponding spectrum in the visible is given by Fig. 2b. This contains, along with already known lines, a new one at 0.569 μm ($S_4^{(2)}$ in Fig. 2b), which was not present when external SH was used to generate nonlinear processes in the visible (SRS or SFWM). Its frequency shift is $\Delta\nu = 1210$ cm^{-1}, which exactly coincides with the frequency shift of the SFWM process in the IR. The output power of the most prominent new line ($\lambda = 0.546$ μm) is approximately 5% of the SH output power.

It is clear that in our case the rise of the new frequencies cannot be attributed to the well-understood effects of frequency doubling and sum-frequency mixing between

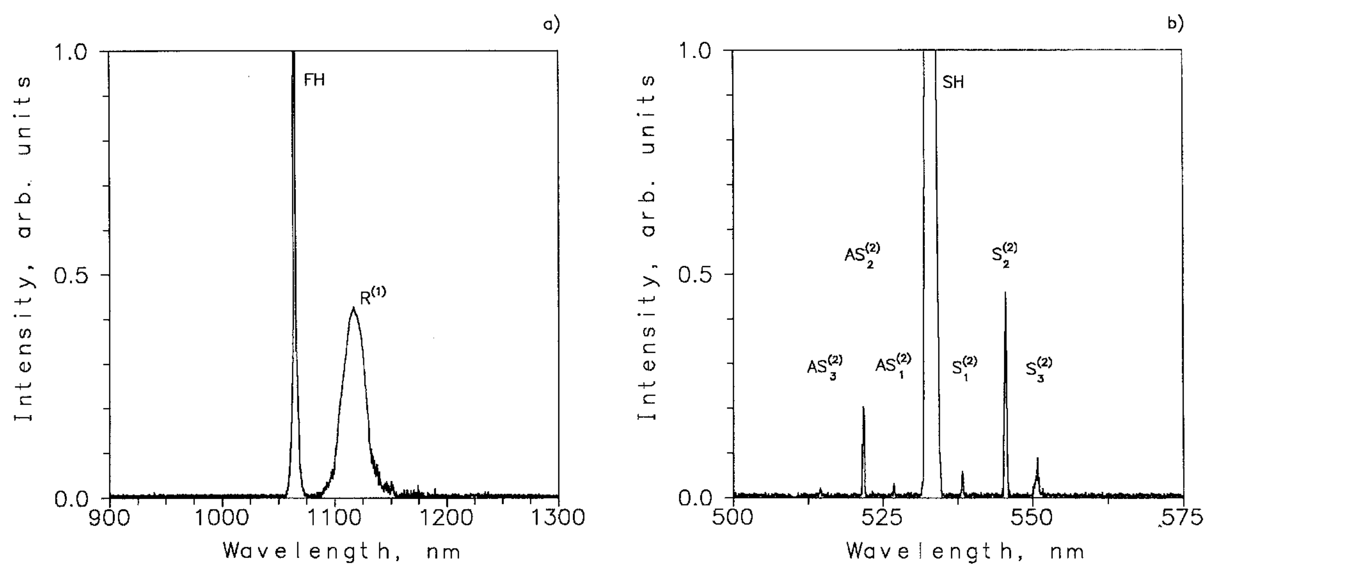

Fig. 1. a The IR output spectrum of the fiber, obtained with average pump powers $P_1 = 7$ mW. **b** The respective visible output spectrum of the fiber.

Table 1. Origin of the spectral lines in the visible range around the SH

Line	Frequency shift	Mixing process	Interactive waves	Energy balance
$AS_1^{(2)}$	+200 cm^{-1}	TWO	FH, $R^{(1)}$ ($\Delta\nu = 200$ cm^{-1}), SH	$\omega_{FH} - \omega_{R^{(1)}} = \omega_{AS_1^{(2)}} - \omega_{SH}$
$S_1^{(2)}$	−200 cm^{-1}	SFWM	SH, SH, $AS_1^{(2)}$	$\omega_{AS_1^{(2)}} - \omega_{SH} = \omega_{SH} - \omega_{S_1^{(2)}}$
$AS_2^{(2)}$	+420 cm^{-1}	TWM	FH, $R^{(1)}$ ($\Delta\nu = 420$ cm^{-1}), SH	$\omega_{FH} - \omega_{R^{(1)}} = \omega_{AS_2^{(2)}} - \omega_{SH}$
$S_2^{(2)}$	−420 cm^{-1}	SFWM	SH, SH, $AS_2^{(2)}$	$\omega_{AS_2^{(2)}} - \omega_{SH} = \omega_{SH} - \omega_{S_2^{(2)}}$
$AS_3^{(2)}$	+640 cm^{-1}	TWM	FH, $R^{(1)}$ ($\Delta\nu = 640$ cm^{-1}), SH	$\omega_{FH} - \omega_{R^{(1)}} = \omega_{AS_3^{(2)}} - \omega_{SH}$
$S_3^{(2)}$	−640 cm^{-1}	SFWM	SH, SH, $AS_3^{(2)}$	$\omega_{AS_3^{(2)}} - \omega_{SH} = \omega_{SH} - \omega_{S_3^{(2)}}$
$S_4^{(2)}$	−1210 cm^{-1}	TWM	FH, $AS_1^{(1)}$, SH	$\omega_{AS_1^{(1)}} - \omega_{FH} = \omega_{SH} - \omega_{S_4^{(2)}}$

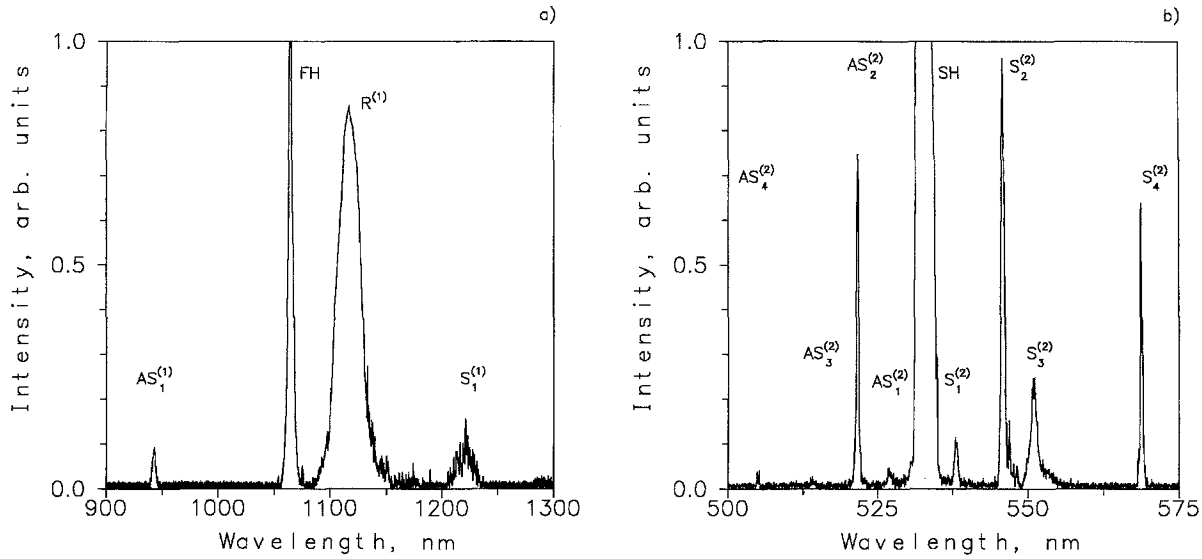

Fig. 2. a The IR output spectrum of the fiber, obtained with average pump powers $P_1 = 10$ mW. **b** The respective visible output spectrum of the fiber.

interacting pump waves different from one that recorded the χ_2 grating [7]. They originate from a nonlinear process, which is characterized by the following essential facts. First of all, the development of most of the new spectral components is evidently connected to the process of SFWM, because their frequency shifts from the SH frequency exactly coincide with the characteristic shifts ($\Delta\nu = \pm 200$, ± 420 and $\pm 640\ \mathrm{cm}^{-1}$) in the SFWM spectrum of the fiber, obtained with an external 0.532 μm pump. At the same time, the power of the generated SH wave in the fiber is far below the threshold power of the SFWM process. Second, a new spectral component whose frequency shift is equal to the characteristic shift $\Delta\nu = 1210\ \mathrm{cm}^{-1}$ in the IR SFWM spectrum of the fiber (i.e. when the fiber is pumped with $\lambda_1 = 1.064$ μm) was observed in the visible range. Third, no spectral components (except the SH) have ever been observed in the visible range when the FH power was below the thresholds of the SFWM and the SRS.

The generation of the multi-frequency visible output spectrum (at $\lambda = 532$ nm) can be qualitatively explained in the framework of the model presented in [3]. Information on spectral components is summarized in Table 1.

Spectral components with frequency shifts ± 200, ± 420, $\pm 640\ \mathrm{cm}^{-1}$ are the result of the two additional nonlinear processes. One involves SH, FH, and a spectral component from SRS at FH, while the second one is a SFWM process of the SH wave. The anti-Stokes components are initiated by the TWM (the first one), while mode selection is the result of SFWM. So, energy transfer from the TWM process in channels of both Stokes and anti-Stokes components of SH is dictated by fiber parameters. We should note that the coherent length of TWM has a small value (several mm), which is the result of a large frequency difference between interactive waves and fiber dispersion.

This interplay between processes is analogous to that observed in [3]. However, there an external SH was used to generate the SFWM in the visible with threefold reduction of the threshold.

In the present case, reduction of the threshold is almost 20–25 times. Since the SH and FH phase difference remains constant over a longer fiber length, the abovementioned effects find their interpretation. This lower threshold will be supported by the absence of a threshold for the TWM process.

The generation of the new component with wavelength $\lambda = 0.569$ μm, observed with an FH pump power of 10 mW (see Fig. 2b line denoted by $S_4^{(2)}$), can be explained in a similar manner. When the threshold for the IR SFWM process is reached, the TWM process will transfer energy to spectral components with the same frequency shifts in the visible. The proposed explanation is confirmed by the fact that it was impossible to obtain the signal at $\lambda = 0.569$ μm when the modal distribution of the FH pump power (controlled by the input angle) was inappropriate for the onset of the IR SFWM process.

In conclusion, a set of new lines in the visible around 0.532 μm was generated from a frequency-doubling fiber pumped with the FH wave only. The frequency shifts of the new lines coincide with the shifts which characterize the usual SFWM processes pumped by an external SH (with a much higher power), or by the FH. The results are explained by an amplification mechanism, which for the first time involves the processes of SFWM in the field of the internally generated SH and additional TWM. To our knowledge, it is for the first time that generation of spectral components with frequency shifts characteristic for the IR SFWM are observed near the SH frequency. The complex spatial dynamics and pump power – output efficiency dependence of the described effect needs further quantitative investigation. The same is true also for the attractive possibility to predetermine the wavelengths of the new signal lines by a proper design and control of the modal content of the fiber or by varying the pump wavelength. Nevertheless, our results clearly demonstrate the potential of the described combined frequency doubling – nonlinear frequency mixing effect for extending the capabilities of the optical fibers as simple and compact nonlinear frequency converters.

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