RGB generation by four-wave mixing in small-core holey fibers

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ABSTRACT

We report the generation of white light comprising red, green, and blue spectral bands from a frequency-doubled fiber laser in submicron-sized cores of microstructured holey fibers. Picosecond pulses of green light are launched into a single suspended core of a silica holey fiber where energy is transferred by an efficient four-wave mixing process into a red and blue sideband whose wavelengths are fixed by birefringent phase matching due to a slight asymmetry of the structure arising during the fiber fabrication. Numerical models of the fiber structure and of the nonlinear processes confirm our interpretation. Finally, we discuss power scaling and limitations of this white light source.

Keywords: Nonlinear fiber optics, RGB generation, microstructured fibers

1. INTRODUCTION

Sources of visible white light based on semiconductor or fiber lasers are currently investigated by a large number of research labs and companies worldwide as a replacement for traditional incandescent light sources for a range of applications. They offer the prospect of better energy efficiency and, in particular, much higher brightness. There are two basic concepts for the generation of white light: supercontinuum sources providing a flat spectrum over a broad range of wavelengths,\(^1\)\(^-\)\(^4\) and red-green-blue (RGB) sources emitting in three relatively narrow spectral bands.\(^5\)\(^,\)\(^6\) While supercontinuum sources are required for applications such as tomography or spectroscopy, RGB sources are preferred, in particular, for image or video projection because of the larger achievable color gamut.

Here we report the demonstration and analysis of a novel RGB white light source.\(^7\) Picosecond pulses from an Yb-doped fiber laser are frequency doubled into the green in a nonlinear crystal and launched into submicron-sized cores of holey fibers, where phase matching between orthogonally polarized modes mediated by a slight fiber asymmetry guarantees a partial conversion of the green pump into red and blue sidebands via a four-wave mixing (FWM) process. The advantages of this RGB source lie in the design flexibility of holey fibers, the high power available from fiber lasers, and the potential for an all-fiber and thus very compact and robust setup if the frequency-doubling crystal is replaced by second-harmonic generation in a poled fiber.\(^8\)

This paper is organized as follows. First, we present the laser setup, the fiber design, and the experimental results on RGB generation in Sec. 2. Section 3 summarizes our numerical models of the fibers and nonlinear pulse propagation which provide a firm basis for the understanding of the reported experimental results. In Sec. 4 we investigate the potential for future optimization of the proposed white light source by analyzing power scaling and various limiting effects. Finally, we summarize our results in Sec. 5.

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2. EXPERIMENTS

2.1 Laser system

Figure 1 shows a schematic of the pump laser system used for our experiments. The pulsed fiber laser consists of a master-oscillator power amplifier (MOPA) source which generates 80 ps pulses at a wavelength of 1060 nm through a sequence of four Yb-doped fiber amplifiers. A gain-switched laser diode is used as a seed which can be operated at repetition rates from 32 MHz to 1 GHz. A maximum of 200 W laser output could be achieved with this system. For the experiments reported here the lowest repetition rate of 32 MHz was employed in order to achieve maximum peak power at lowest average power. Scaling to higher powers will be discussed in Sec. 4. The output beam of the MOPA is then collimated and polarization controlled and focused into a 15 mm LBO crystal for frequency doubling. After the crystal, a highly selective dielectric mirror is used to separate the remaining infrared light from the green second harmonic at 530 nm. While up to 80 W of green light could be observed from this system, here the power was restricted to 2 W and a peak power of 780 W in order to avoid damaging the nonlinear holey fiber.

2.2 Holey fiber design

The green output beam of the of the laser source described above is then passed through another half-wave plate for polarization control and is then focused into a single submicron-sized core of a microstructured holey fiber.

Five different holey fibers (labeled A to E in the following) of 1 m length each have been used for our experiments, a typical SEM image is shown in Fig. 2. All of them were photonic bandgap fibers initially designed to guide light in the hollow air core at wavelengths of 1070, 1210, 1550, 1800, and 2000 nm, respectively. Fibers A and B were drawn from one preform, fibers C, D, and E from another. However, the geometry was similar in all cases and the fibers differ mainly by an overall scaling factor. The ratio of hole size to hole-to-hole spacing (pitch) $d/\Lambda$ was about 0.935, and $\Lambda$ was between 2.5 $\mu$m for fiber A and 4.7 $\mu$m for fiber E.

The RGB generation experiments reported here were performed within single small, secondary silica cores of the fiber claddings as indicated by the white circle in Fig. 2. The radii of these cores, as measured by an
inscribed circle, range form about 200 nm to 400 nm, corresponding to a nonlinear parameter $\gamma$ of about 400 to 200 W$^{-1}$km$^{-1}$ at 530 nm wavelength. Note that the large central hole of these fibers do not participate in the RGB generation process itself. However, their presence ensures a nonuniform expansion of the cladding holes and therefore of the secondary cores during the fiber drawing process, which eventually provides the necessary asymmetry for birefringent phase matching.

2.3 Experimental results

Figure 3 shows sample spectra measured at the output of 1 m long holey fibers as described above. For all fibers A to E we observe three distinct wavelength bands, one in the red, one in the blue, and the remaining green pump. Different fibers exhibit different wavelength separation between the sidebands. However, a similar variation was also found when the pump light was launched into various secondary cores of a single fiber, for example, fiber C could generate sidebands separated by anything between 100 nm and 300 nm. We also confirmed experimentally that all spectral components of the RGB light were indeed emitted by a single secondary core at the fiber output. Moreover, it was also confirmed that the red and blue sidebands were polarized orthogonally to the green pump, as expected for FWM with birefringent phase matching.\textsuperscript{10,11} Finally, the sidebands satisfy the FWM energy conservation condition

$$2\omega_g = \omega_r + \omega_b,$$

where $\omega_{r,g,b}$ denotes the angular frequency of the red, green, and blue light, respectively. By careful fiber fabrication and/or selection, it is therefore possible to optimize the wavelengths of the RGB light. For example, 530 nm green light can be used to generate simultaneously 470 nm blue and 610 nm red.

The spectra shown in Fig. 3 also clearly exhibit one or two Raman shifted Stokes peaks of the green pump. This constitutes a competing nonlinear process to FWM and can ultimately limit the conversion efficiency, see Sec. 4.

The total output power observed was typically in excess of 300 mW from a 2 W green pump. For example for the case of fiber C, a total output power of 360 mW was observed, with 47, 292, and 21 mW of blue, green, and red power, respectively. A cut-back measurement was also performed and showed that RGB generation occurred essentially during the first 30 cm of fiber.
3. MODELING

In order to better understand the system and to confirm the nature of the nonlinear RGB generating process we also performed a range of numerical simulations.

In a first step, we took high resolution SEM images of the holey fibers, such as shown in Fig. 4. We then scanned a magnified detail comprising two secondary cores to obtain a realistic contour of the fiber structure which was subsequently used to calculate the mode structure. For these simulations we used a full-vectorial mode solver based on the Finite Element Method. The calculated effective refractive index \( n_{\text{eff}} \) for the two orthogonally polarized fundamental modes of a single core of fiber C is shown in Fig. 5. Due to the slight asymmetry of the fiber structure in the vicinity of the central air hole the two polarization modes are not degenerate, but exhibit a form birefringence

\[
B = |n_{\text{eff},1} - n_{\text{eff},2}| \approx 2.5 \times 10^{-4}
\]

at 530 nm wavelength.

Because of this nonvanishing value of \( B \), phase matched FWM can occur where the pump is in one polarization mode and signal and idler are in the other. The phase matching condition amounts to

\[
2\omega_p n_{\text{eff},1}(\omega_g) = \omega_r n_{\text{eff},2}(\omega_r) + \omega_b n_{\text{eff},2}(\omega_b).
\]

For a given pump wavelength, Eqs. (1) and (3) form a set of nonlinear equations which can be solved for the frequencies (wavelengths) of the resonantly generated red and blue sidebands. The results for fiber C as a function
of pump wavelength are shown in Fig. 5. In accordance with the experimental results, the simulations predict sidebands at approximately 470 nm and 610 nm for pumping at 530 nm, which confirms our interpretation of the RGB generation by FWM using birefringent phase matching.

4. POWER SCALING

In this section we will review several effects which may limit the maximum power achievable through such an RGB source and we will discuss possible improvements.

4.1 Damage threshold

A fundamental limitation of the maximum output power is given by the optical power the fiber can sustain without experiencing any damage. Since we are working with submicron-sized fiber cores, this restriction will be much more severe than in standard fiber lasers or amplifiers.

The damage fluence of fused silica can be approximated by

$$ F \approx 1.29 \sqrt{\tau} \ J cm^{-2} ps^{-1/2} \quad (4) $$

for pulse durations $\tau$ in the ps regime.\(^\text{13}\) Assuming a fiber core area of about 0.25 $\mu m^2$ (0.3 $\mu m$ radius), a pulse duration of 80 ps, and a repetition rate of 32 MHz, we obtain a damage average power of 0.9 W, whereas a fiber core of 1 $\mu m^2$ allows for up to 3.7 W. Further power scaling can be achieved in two ways by modifying the pump laser only, but using the same fiber: (i) By increasing the repetition rate, which leads to a linear increase of the damage power, or (2) by increasing the pulse length. Note however that in the latter case the maximum peak power decreases with increasing pulse duration as $\tau^{-1/2}$, and thus the corresponding reduction of the nonlinear effects has to be compensated by using a longer fiber length, which imposes more stringent conditions on fiber uniformity and fiber loss.

4.2 Core size

For our experiments we used holey fibers which were available to us at the time. A holey fiber specifically designed for this application may thus be another option to increase the damage power. In particular, this could be achieved with larger core sizes. However, the main consideration in this case will be to retain the relatively large birefringence required for phase matching which we found to be of the order of $B \sim 5 \times 10^{-4}$. For the specific structure of the secondary cores in our fibers, a spatial asymmetry of 10-20% is therefore necessary.\(^\text{7}\)

One may thus consider fiber cores with higher aspect ratios of the transverse dimensions and of different design, in particular with thinner connecting struts to provide better mode confinement. As an extreme example
of what might be achievable with this approach, we calculated the birefringence of elliptical fibers of micrometer size suspended in air. In Fig. 6 we show the results for three different values of $\varepsilon = d_1/d_2$, where $d_{1,2}$ are the two main axes of the elliptical fiber, as a function of the fiber cross section area. As expected, $B$ decreases rapidly with increasing fiber area. Nevertheless, the results indicate that highly asymmetric fibers of $\varepsilon = 2$ exhibit a birefringence of $B \sim 0.005$ for cross sections as large as 20 $\mu$m$^2$. Note, however, that at this size a fiber surrounded by air will support a large number of modes and it will therefore be challenging to achieve single-mode operation. While an air-suspended elliptical fiber will not be a viable design for an actual RGB source, we conclude that there is significant scope for increasing the fiber size compared to the fibers used by us, potentially by up to a factor of ten, and thus an increase of the damage power by one order of magnitude.

### 4.3 Conversion efficiency of birefringent four-wave mixing

The fact that in our system the red and blue sidebands are orthogonally polarized to the green pump is detrimental to the nonlinear conversion process, since the nonlinear coupling between orthogonally polarized modes is only one third of the coupling between parallel polarizations. Thus, the four-wave mixing efficiency is reduced while self-phase modulation (SPM), which leads to dephasing of the various spectral bands, remains unchanged.

Let us consider a simple cw model to estimate the maximum conversion efficiency. Here we assume that the green and the red/blue modes have orthogonal linear polarization but otherwise show the same transverse mode profile. In this case, nonlinear light propagation is described by three coupled differential equations,

\begin{align}
\frac{dA_g}{dz} &= i\frac{2\pi n_2}{\lambda_g A_{\text{eff}}} \left[ |A_g|^2 A_g + \frac{2}{3} (|A_r|^2 + |A_b|^2) A_g + \frac{2}{3} A_r A_b A_g^* e^{i\Delta k z} \right], \quad (5) \\
\frac{dA_r}{dz} &= i\frac{2\pi n_2}{\lambda_r A_{\text{eff}}} \left[ |A_r|^2 A_r + \frac{2}{3} (|A_g|^2 + 3|A_b|^2) A_r + \frac{1}{3} A_g^2 A_b^* e^{-i\Delta k z} \right], \quad (6) \\
\frac{dA_b}{dz} &= i\frac{2\pi n_2}{\lambda_b A_{\text{eff}}} \left[ |A_b|^2 A_b + \frac{2}{3} (|A_g|^2 + 3|A_r|^2) A_b + \frac{1}{3} A_g^2 A_r^* e^{-i\Delta k z} \right], \quad (7)
\end{align}

where $A_{r,g,b}$ is the slowly varying amplitude of the red, green, and blue light, $n_2 = 2.5 \times 10^{-20} \text{ m}^2/\text{W}$ is the nonlinear refractive index of silica, $A_{\text{eff}}$ is the effective mode area, and $\Delta k = k_r + k_b - 2k_g$ is the FWM phase mismatch. Figure 7 shows the solution of Eqs. (5)-(7) for parameters close to our experiment. In this cw model, power oscillates periodically with distance between the pump and the FWM sidebands, but the pump beam is never entirely depleted. The phase mismatch $\Delta k$ for this simulations was chosen to optimize the power transfer. At the point of maximum sideband power we find 158 W red, 134 W green, and 205 W blue, i.e.,

![Figure 7: Power transfer between green pump ($\lambda_g = 530 \text{ nm}$, solid line) and red ($\lambda_r = 610 \text{ nm}$, dash-dotted) and blue ($\lambda_b = 470 \text{ nm}$, dashed) spectral bands by FWM. Left: Propagation over 1 m of fiber; right: Detail. Here $A_{\text{eff}} = 0.25 \mu m^2$, $\Delta k = 7 \text{ m}^{-1}$.


approximately one third of the total power in each channel. This would be ideal for an RGB source and indicates that important improvements of the conversion efficiency observed in our experiments, see Sec. 2.3, can be achieved in principle. However, the dynamics in the pulsed regime is much more complicated, and fabrication and experimental uncertainties may limit power conversion to lower levels in practice.

4.4 Competing nonlinearity: Raman effect

As already mentioned in Sec. 2, in our experiments we always observed one or two Raman sidebands of the green pump together with the red and blue spectral sidebands. In contrast to the FWM process, stimulated Raman scattering is not phase sensitive and is thus not susceptible to SPM-induced phase shifts or longitudinal fiber nonuniformity. Raman scattering may therefore restrict RGB generation. In the following we derive an estimate for this limit.

First, we estimate the small signal gain for the FWM process. From Eq. (6) we obtain a propagation equation for the power $|A_r|^2$ of the red sideband. In the limit of a small signal, assuming optimum phase matching, and utilizing the fact that the ratio of the blue and red power is fixed by the ratio of the blue and red photon energies, we obtain

$$\frac{d|A_r|^2}{dz} = \frac{2}{3} \frac{2\pi n_2}{\lambda_r \lambda_b A_{\text{eff}}} |A_g|^2 |A_r|^2$$

and thus find the FWM gain

$$g_{\text{FWM}} = \frac{2}{3} \frac{2\pi n_2}{\lambda_r \lambda_b A_{\text{eff}}} |A_g|^2 .$$

For the parameters of Fig. 7, we get $g_{\text{FWM}} = 391 \text{ m}^{-1}$. This has to be compared with the peak of the Raman gain of approximately $10^{-13} \text{ m/W}$ at 1 $\mu$m wavelength. Accounting for the inverse relationship with wavelength, the Raman gain in our situation becomes

$$g_R = \frac{10^{-19} \text{ m}^2/\text{W}}{\lambda_g A_{\text{eff}}} |A_g|^2$$

which for our parameters gives $g_{\text{FWM}} = 377 \text{ m}^{-1}$. The Raman gain is thus equal to the FWM gain which implies that even in the case of optimized FWM phase matching the first Raman Stokes order of the pump exhibits the same optical power as the red and blue sidebands. We therefore estimate that the maximum power in each of the red and blue sidebands will be reduced from one third of the total power, as estimated in the previous section, to approximately one fourth.

5. CONCLUSIONS

In conclusion, we demonstrated a source of white light based on a picosecond green pump obtained from a frequency-doubled Yb-doped fiber laser which is converted by nonlinear effects in submicron-sized holey fibers. The generating process has been identified as four-wave mixing with birefringent phase matching mediated by a slight fiber asymmetry. A total output power of 360 mW was observed, with 47, 292, and 21 mW of blue, green, and red power, respectively.

Our theoretical and numerical analysis indicates that the maximum conversion efficiency of power from the green to the red and blue sidebands is limited by two fundamental effects: (i) The FWM process with orthogonally polarized pump and signal/idler suffers from dephasing by self-phase modulation; (ii) Stimulated Raman scattering constitutes a competing nonlinearity to FWM with near-identical small signal gain. We therefore estimate that in an optimized system the output will be limited to 25% red, 50% green, and 25% blue.

For the pump laser and the holey fibers used in our experiments, the maximum achievable RGB power is limited by the damage threshold of the submicron fiber cores to about 1 W. However, our calculations suggest that highly asymmetric fibers with cross sections of up to 20 $\mu$m$^2$ can still provide the significant birefringence required for our RGB scheme. Together with an increased repetition rate of the pump laser, we therefore envisage that specially designed systems may be power scaled to the tens of Watts level or potentially even beyond 100 W.
Finally, we emphasize that while our pump source used free space optics for the second harmonic generation in a nonlinear crystal, this step could in the future be performed within a periodically poled fiber. This would allow for the possibility of an all-fiber RGB source with all the associated advantages of compactness and robustness.

REFERENCES