Kiran

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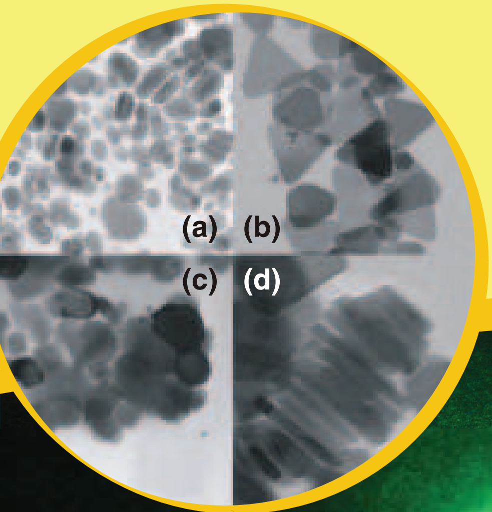
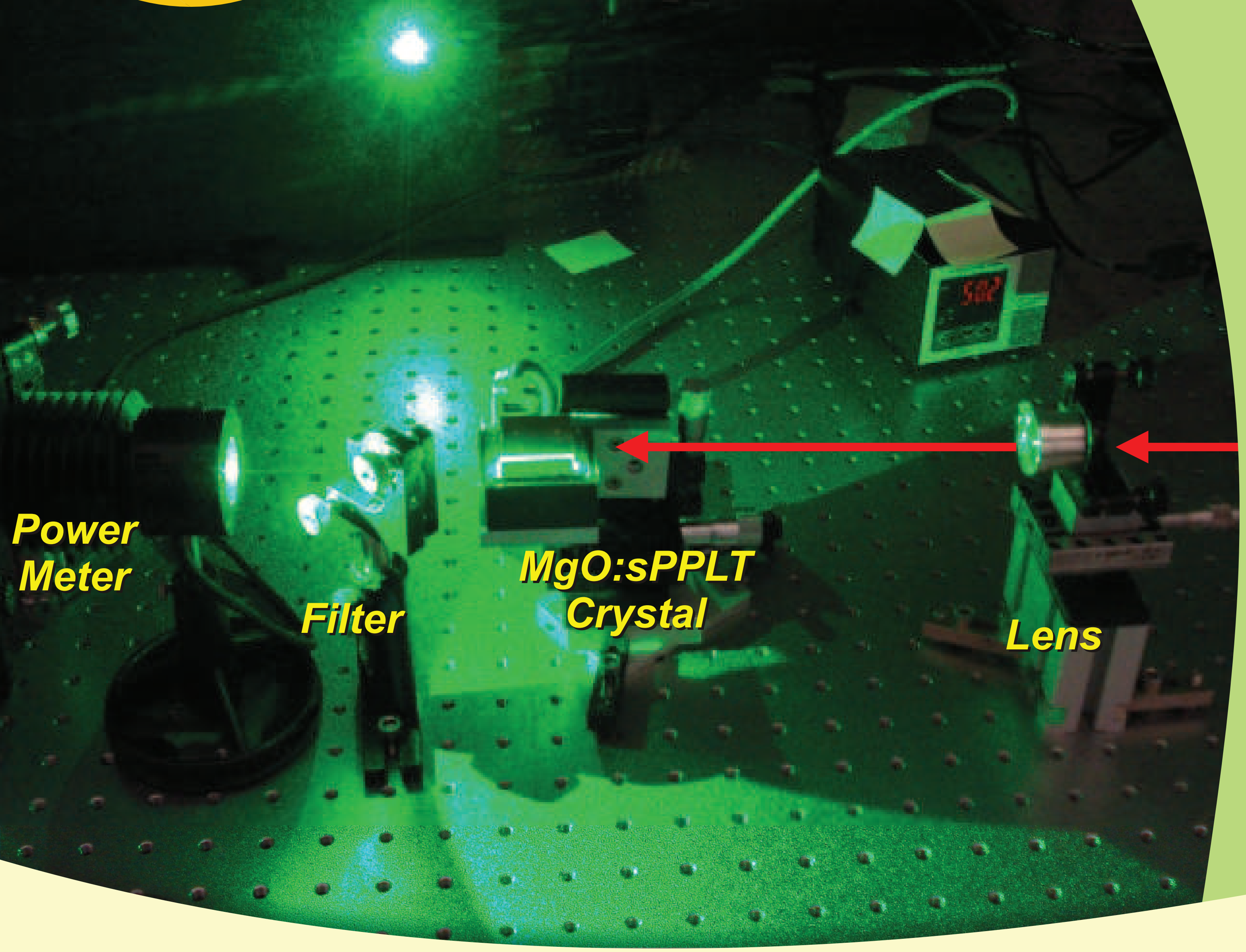


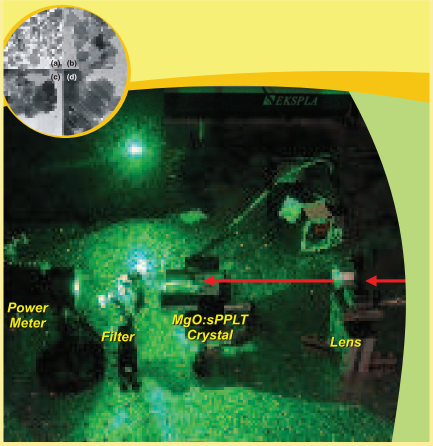


Special Issue on Best Theses and Posters at National Laser Symposium - 09

ILA Executive Committee

Editorial Team of Kiran

Cover Photo :



For the main image on the cover page:

The photograph shows the experimental set up to obtain the green source by frequency doubling cw fiber laser using MgO doped periodically poled stoichiometric lithium tantalate crystal. The experiment shows an efficient method of generating high-power, narrow-linewidth, green sources using single-pass second harmonic generation of the high power, cw, fiber lasers using periodically poled potassium titanyl phosphate and MgO doped periodically poled stoichiometric lithium tantalate nonlinear optical crystals. Details are given on pg. 2-6.

For the image in the inset (top left corner):

The TEM pictures of chemically prepared silver nanoplatelets. (a), (b), and (c) are for sample having in-plane dipole peaks at 506, 660 and 780 nm, respectively. (d) shows a bunch of standing platelets from which thickness of platelets (having peak at 780 nm) can be estimated. The aspect ratios of the platelets are 1.7, 3.7, and 7 for in-plane dipole peaks at 506, 660 and 780 nm, respectively. Details are given on pg. 7-12.

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Contents

From The Editor...

In this issue of 'Kiran' we are presenting a compendium of articles based on the best theses and posters awarded by the Indian Laser Association (ILA) at the Ninth DAE-BRNS National Laser Symposium (NLS-09) organized at Bhabha Atomic Research Centre, Mumbai during January 13 to 16, 2010. On behalf of the editorial committee and my own behalf I take this opportunity to congratulate the authors of these articles for receiving the awards.

This year is particularly significant for the laser community all over the world because it marks the 50th anniversary of the invention of a laser, which was accomplished in 1960 by Prof. Theodore Maiman. We are planning to bring out a special issue of Kiran by the end of this year to commemorate this historic invention. The members of ILA are solicited to send their suggestions, articles and news items for this important issue of 'Kiran' by the end of October 2010.

In the last issue of 'Kiran' we proposed to introduce a column on 'Letters to Editor' wherein the readers could express their opinion on topical issues of general interest or present their comments on the articles published in 'Kiran'. The readers are invited to send their write-ups for this column. Idea was also mooted to initiate a series on 'Thesis Articles' on a regular basis in which the PhD scholars and their guides can present the significant results of the research work carried out as part of their recently completed PhD theses in the form of articles. The PhD scholars and their guides are invited to send the thesis articles. As you know, your support and efforts are crucial for making 'Kiran' vibrant.

I would like to invite your attention to the first announcement about the tenth DAE-BRNS National Laser Symposium inserted on page 35 and reports on the NLS-09 and DAE-BRNS 5th National Symposium on Pulsed Laser Deposition of Thin Films and Nanostructured Materials presented on pages from 32-34 of this issue. I hope you will find this issue of 'Kiran' both interesting and useful.

Lalit M. Kukreja
April 30, 2010

Articles based on Best Thesis Presented at NLS-09

High-power, Continuous-wave, Optical Parametric Oscillators from Visible to Near-infrared

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Introduction

The laser is one of the inventions that brought science very much ahead in the last few decades due to its wide variety of scientific and technological applications. Despite the successful use of the laser for nearly 50 years, unavailability of the suitable gain materials restricted the develop of laser systems that can cover many regions of the optical spectrum from ultraviolet (UV) and visible to the near- and mid-infrared wavelength range, with potential applications in the fields such as spectroscopy, remote sensing, trace gas detection, and many more.

On the other hand, optical parametric oscillators (OPOs) have become a standard device to convert a fixed laser wavelength to wide band of coherent radiation ranging from visible to far-IR in all time scales from continuous-wave (cw) to femtosecond. This thesis presents the development of a new class of high-power, cw OPOs with extended tunability from visible to near-infrared (near-IR). Development of cw OPOs in singly-resonant oscillator (SRO) configurations, the focus of this thesis, is challenging due to the high threshold pump power (several watts). In addition, with visible pumping, photorefractive effect and thermal lensing effects become important issues to overcome. Therefore, the realization of practical cw SROs requires optimal cavity design, suitable nonlinear materials, and high-power laser with high spectral and spatial quality. The vast majority of cw SROs developed to date have been based on periodically-poled lithium niobate (PPLN), providing spectral coverage from ~1μm to the absorption edge of the material near ~5 μm [1–4]. Photorefractive damage induced by the visible pump or signal radiation precludes the use of PPLN for wavelengths below ~1 μm. Therefore, the development of cw OPOs for the visible to the near-IR regions, especially in high-power SRO configurations, necessitates the search for new QPM materials. Periodically-poled lithium tantalate (PPLT) is one such promising material due to its increased resistance to photorefractive damage. Although PPLT has been used to demonstrate pulsed OPO [5] and cw PE-SROs [6], a stable, widely-tunable, single-frequency cw SRO pumped in the visible has not yet been demonstrated except for those presented in this thesis and subsequently [7, 8] afterwards.

The generic approach of my thesis work is shown in the Fig. 1. The thesis can be divided into five parts. **1.** We used a commercial cw, solid-state green laser to pump the cw SRO generating cw, single-frequency radiation tunable in the near-IR [9, 10]. Although the cw SRO can provide optical radiation across 848-1430 nm, the high output power was only available across 1104-1430 nm (idler) due to the high reflectivity of the cavity mirrors at resonant (signal) wavelength range in order to sustain SRO operation. **2.** Using a finite output coupling of the resonant wave, we have extended the available practical output power across the entire tuning range [11]. **3.** To

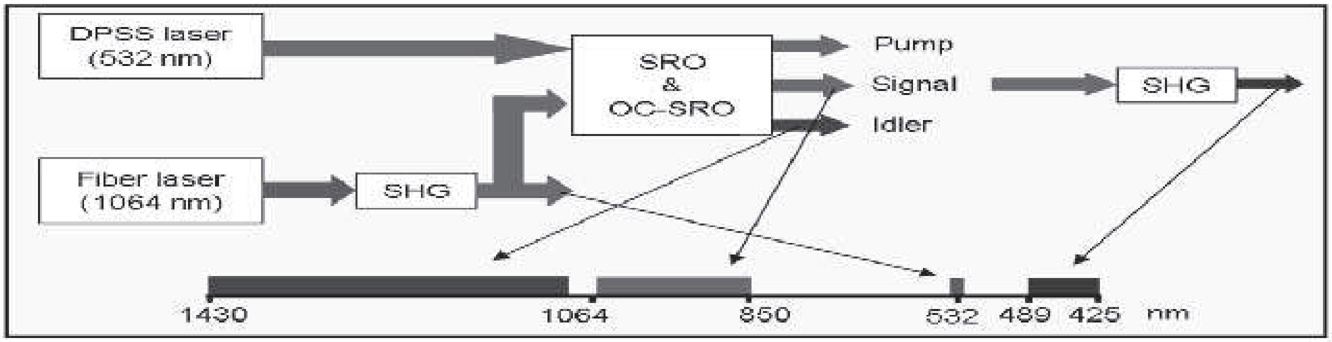

Fig. 1: Concept of the development of tunable light sources

extend cw SRO operation into the visible, we have frequency-doubling the high power intracavity signal radiation of the cw SRO to generated widely tunable blue radiation [12]. There is only one commercially available high-power green laser (Coherent Verdi) used to pump visible and near-IR cw SROs. **4.** We therefore have developed alternative high-power green lasers by single-pass frequency-doubling of a fiber laser in two different periodically-poled crystals [13-15]. **5.** Using such a home-made green source, we demonstrated cw SRO in the near-IR [16].

Development of CW SRO (850-1430 nm) [9, 10]

High-power, single-frequency, cw SROs based on 30-mm-long MgO-doped, stoichiometrically grown, periodically-poled LiTaO$_3$ (MgO:sPPLT) have been developed. The oscillators were pumped in the green by a frequency-doubled, cw diode pumped Nd:YVO$_4$ laser at 532 nm. With a single grating period (Λ) of 7.97 μm, continuous signal and idler covering the 848-1430 nm region is obtained by temperature tuning between 52 ^{o}C and 248 ^{o}C with the results shown in Fig. 2. The small gap in the tuning curve near degeneracy due to the reflectivity fall-off of the cavity mirrors to avoid doubly resonance condition. For single-frequency operation of the cw SRO across 848-1430 nm, we have used a compact ring cavity configuration and an uncoated fused silica etalon inside the cavity for fine frequency control. Using the same MgO:sPPLT crystal, the SRO oscillation threshold of 2.84 W has been obtained, and a single-pass idler powers in excess of 1.59 W have been generated over 1104-1430 nm with a maximum extraction efficiency of the SRO of 25.2% and pump depletions as much as 67%. Towards the extreme of the tuning range the idler power decreases due to 1) higher thermal lensing effect which restricts the perfect mode-matching between the pump and signal, 2) reduction in the gain away from the degeneracy and 3) higher reflection losses in the crystal coatings. The single-frequency idler output has an instantaneous linewidth of ~7 MHz. Under free-running conditions and in the absence of thermal isolation, the idler power exhibits a peak-to-peak stability of 16% over 5 hours. This power fluctuation, attributed mainly due to the changes in the laboratory environment and the thermal instability of the oven which, can further be improved by isolating the SRO system from laboratory environment along with improved temperature controlled oven. With the active frequency stabilization we can perform fine frequency tuning of the SRO, making the SRO a useful source for different applications including spectroscopy and trace gas sensing.

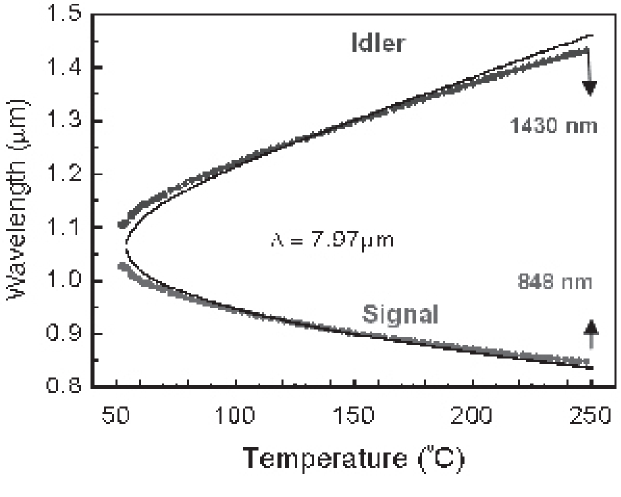

Fig. 2: Temperature tuning curve of the green pumped cw SRO based on MgO:sPPLT crystal of single grating period (Λ=7.97μm)

CW SRO with resonant wave coupling [11]

We have demonstrated that by deploying finite output coupling of the resonant wave in a cw SRO, it is possible to enhance the overall output power, extraction efficiency, useful tuning range and spectral purity with little or no sacrifice to threshold, idler power, or pump depletion. The out-coupled SRO (OC-SRO) is configured in a compact ring cavity, comprising two concave mirrors (*r*=50mm) and two plane mirrors. All the mirrors are HR (R>99%) at signal wavelengths and HT (T>95%) at idler and pump wavelength except one of the

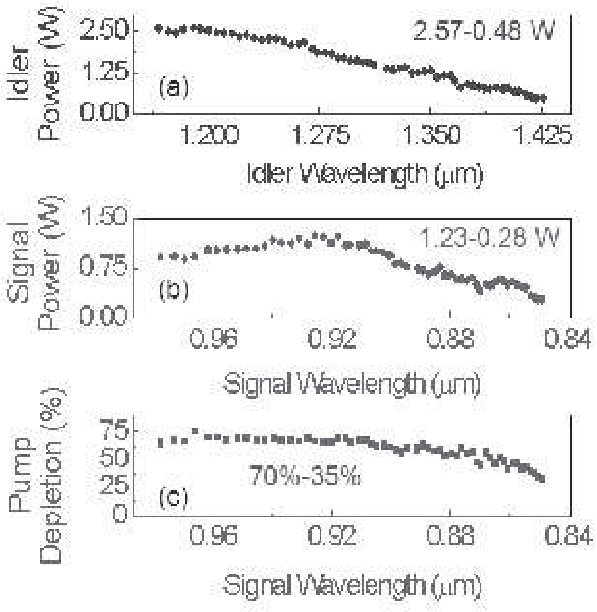

Fig. 3: (a) Idler power, (b) signal power, and (c) pump depletion of the OC-SRO.

plane mirror has finite transmission (T=0.74-1.04%) at the signal wavelength. The output power and the pump depletion of the OC-SRO are shown in Fig. 3. As evident in Fig 3(a), the idler power varies from 2.57 W at 1167 nm to 2.59 W at 1190 nm, to 480 mW at 1427 nm. The signal output varies from 915 mW at 978 nm to 1.23 W at 925 nm, to 278 mW at 848 nm, as shown in Fig. 3 (b). The maximum total output power and extraction efficiency across the tuning range are now 3.6 W and 40%, respectively, at 1190 nm (idler) and 962 nm (signal) at 83°C, representing a 1.08 W increase in output power and 10% in extraction efficiency. The pump depletion again remaining close to ~70% over most of the tuning range before declining to ~35% at the extreme of the tuning range (Fig 3(c)). Thus, despite the increased signal coupling, the idler power and pump depletion in OC-SRO remain similar to the SRO [11]. Importantly, however, the OC-SRO can now provide substantial signal powers of up to 1.23 W across the tuning range. From the Fig. 3 (b), the optimum value of output coupling in the present device is 1.04% at 925 nm. We have also observed improved spectral purity of the resonant signal (3 MHz) compared with the non-resonant idler (7 MHz), implying the advantage of exploiting the resonant out-coupled wave for spectroscopic applications. Besides, the thermal effects due to the absorption of the high signal power resonating inside the cavity can be overcome by reducing the resonating signal using output coupling, with little sacrifice of oscillation threshold (increased by 540 mW compared to SRO). In near-degenerate operation, for example, it could provide improved output power in a single beam with a finite spectrum, which could be useful for cascaded pumping of mid-infrared OPOs or in applications were high-power and broadband cw sources are simultaneously required.

Generation of blue radiation [12]

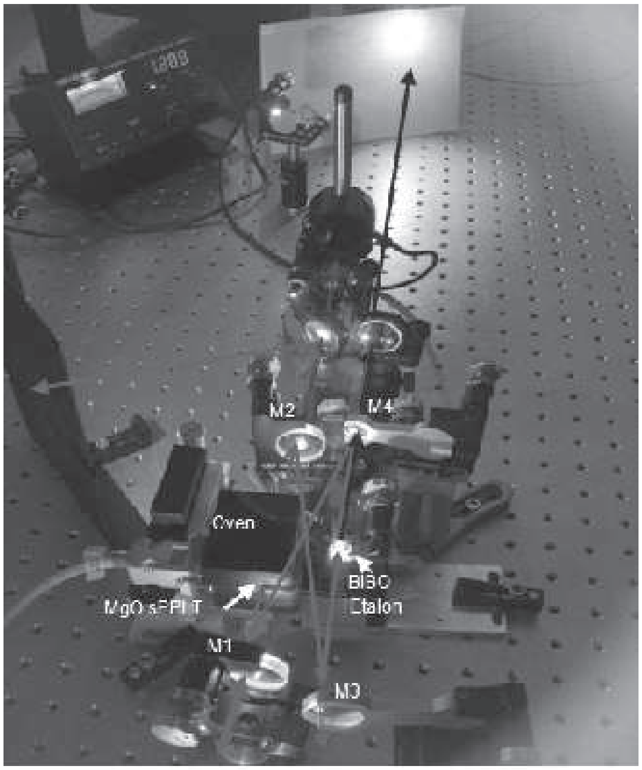

Fig. 4: Photograph of the experimental setup for cw, blue radiation.

To extend cw SRO operation into the visible, we have used internal second-harmonic-generation of the resonant near-infrared signal radiation of the cw SRO demonstrating a practical solid-state laser source tunable across the 425-489 nm spectral range in the blue. Figure 4 shows the photograph of the intracavity frequency-doubled SRO in the blue. The SRO is consisted in compact ring cavity with two curve mirrors (M_1 and M_2) (r=10 cm) and two plane mirrors (M_3 and M_4). All the mirrors are HR (R>99%) for signal wavelength range and HT (T>90%) for idler and pump radiation. Mirror M_4 is also highly transmitting (T>95%) for the blue wavelength range. The MgO:sPPLT crystal (as previously used) is placed between the two curve mirrors to obtain SRO operation. A-5 mm long and 4 mm × 8 mm in aperture BIBO crystal is placed at the second beam waist of the cavity to frequency double the intracavity signal wavelengths. The crystal is cut for type-I phase matching (*ee* *o*) in the optical *yz* plane (φ=90°) at an internal angle θ=160° at normal incidence (*deff*~3.4 pm/V), corresponding to a fundamental wavelength of ~920 nm. By varying the MgO:sPPLT crystal temperature from 71°C to 240°C, the signal could be continuously tuned from 978 to 850 nm (idler from 1167 to 1422 nm) [9]. The corresponding SHG wavelengths from 489 to 425 nm are generated by varying the internal angle of the BIBO crystal from 163.8° to 155.2°. This is to our knowledge by far the broadest tuning range of any cw source in the blue. The source exhibits high output power of up to 1.27 W in spatial beam quality over the entire tuning range in the blue region with additional optical radiation with practical power >100 mW over 850-915 nm wavelength range, with 970 mW at 900 nm, and high-power up to 2.6 W across the wavelength range of 1167-1422 nm. The blue source exhibits mode-hop-free, single-frequency (linewidth ~8.5 MHz) radiation with a natural frequency stability better than 280 MHz, limited by the resolution of the wavemeter. The demonstrated tuning range of the blue is at present limited by the grating period of the MgO:sPPLT crystal, and so can be extended to cover the entire range of 300-530 nm using alternative gratings. The use of other grating periods will also enable blue generation at lower temperatures, reducing the effects of thermal lensing, and thus extending the higher powers to shorter wavelengths. Moreover, by resonating the idler wave in the 1140-1420 nm range, tunable generation across the 570-710 nm will also be possible, making this a promising approach for the generation of high-power, widely tunable, cw radiation across the 300-700 nm spectral range.

Development of high-power green sources [13-15]

We have demonstrated efficient, high-power, narrow-linewidth, green sources in compact and practical design using single-pass SHG of the high-power, cw, fiber lasers using PPKTP and MgO:sPPLT as nonlinear crystals. Figure 5 shows the photograph of the green source obtained by frequency doubling cw fiber laser in MgO:sPPLT crystal. To optimize the SHG of a 30-mm-long MgO:sPPLT crystal, we used several focusing conditions corresponding to different values of the focusing parameter, [16] and measured the maximum generated second-harmonic (SH) powers. Interestingly, the extrapolated power curve has a clear peak near (ξ=2.84), corresponding to the theoretical prediction for optimum SHG in the cw (or long-pulse) limit [16]. Constrained by the available lens we operated the source at ξ=2.48, and have generated 9.6 W of cw, single-mode radiation at 532 nm with a single-pass conversion efficiency as high as 32.7% using simple, single-pass SHG of a cw, single-frequency Yb-fiber laser (30 W) near room- temperature (50 °C). This source exhibits a natural peak-to-peak power stability better than 9% over 13 hours with an instantaneous linewidth of 6.5 MHz and frequency-stability better than 32 MHz over 30 minutes. We have generated green output beam with TEM_{00} spatial profile with M^2 <1.33 at all fundamental powers. With more stringent thermal control and optimized focusing, further improvements in green power and efficiency as well as power scaling are feasible. There is no deterioration in the output power and spatial beam quality of the green source during repeated measurements and with continuous operation over 13 h, confirming stable power and robust TEM_{00} spatial mode, making the device particularly attractive as a pump source for cw SROs as well as cw and mode-locked Ti:sapphire lasers. Using 17 mm long PPKTP crystal containing a single grating with period of 9.01 μm, we generate 6.2 W of cw radiation at 532 nm for a fundamental power of 29.75 W at a single-pass conversion efficiency of 20.8%. However, at fundamental > 20 W, thermal effects degrade the green power with time, results the PPKTP based reliable green source at lower power.

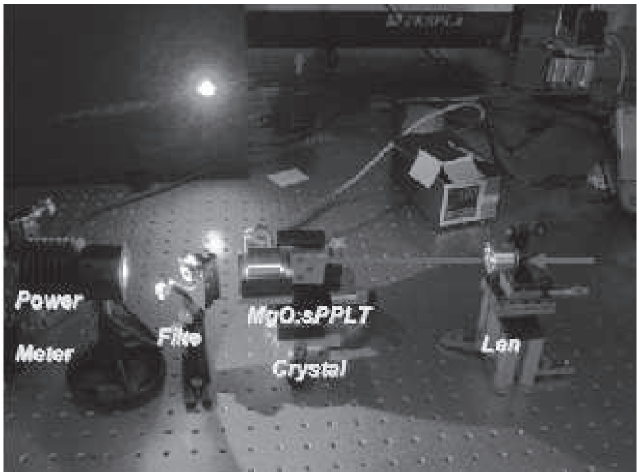

Fig. 5: Photograph of the single-pass, cw, frequency-doubled fiber based green source

Demonstration of CW SRO using frequency-doubled green fiber laser [17]

Using the home made compact, high-power, cw, single-pass frequency-doubled Yb-fiber laser green source, we have demonstrated a cw OC-SRO based on MgO:sPPLT, providing continuously tunable radiation across 855-1408 nm. The non-resonant idler output of the OC-SRO exhibits a maximum power up to 2 W in a TEM_{00} spatial mode (M^2 <1.26), with a peak-to-peak power stability <11.7% over 40 minutes. Optimum output coupling (T=1.04%) of the resonant signal of the cw OC-SRO provides single-frequency signal radiation

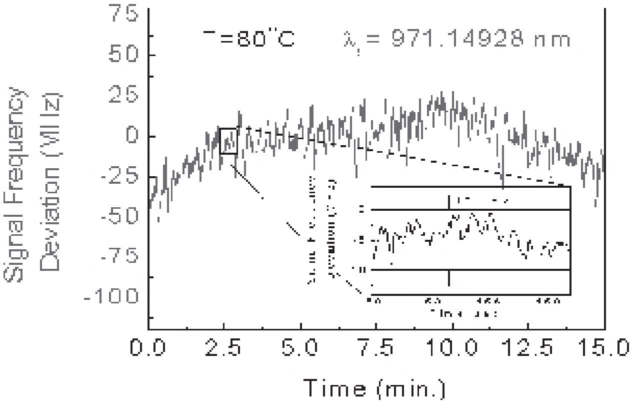

Fig. 6: Long-term frequency stability of signal at wavelength 971.14928 nm for crystal temperature of 80°C over 15 min and (inset) short-term frequency stability over 10 sec.

up to a power of 800 mW, with a peak-to-peak power stability <10.7% over 40 minutes in a TEM_{00} spatial mode with M^2 <1.52. We verified single-frequency nature of the generated signal and idler using a confocal interferometer (FSR=1 GHz, finesse~400). The frequency stability of the out-coupled signal at 971 nm, measured at 600 mW using a wavemeter (High Finesse, WS/U-30), is shown in Fig. 6. The signal frequency exhibits a passive peak-to-peak stability ~75 MHz over 15 minutes, with a nearly periodic variation in frequency deviation also evident with time. The inset of Fig. 6 shows the short-term frequency stability, where we can observe stable signal frequency to <10 MHz (limited by the relative accuracy of the wavemeter) over 10 s, before shifting to another frequency. We record similar behavior across the signal tuning range. With increased pump power to the OC-SRO using optimized optics and reduced thermal lensing with loose pump focusing, further improvements in the output power of the OC-SRO across the tuning range are feasible. Simultaneous, stable, single-frequency operation and high output power performance over a tuning range of 553 nm in good spatial beam quality, make the OC-SRO an attractive source particularly for high-resolution spectroscopic applications.

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