CWF32 Fig. 1. Setup for the frequency conversion of a laser diode MOPA with beam shaping system, extra-cavity high-Q SHG-ring resonator with LBO crystal and spatially and spectrally selective feedback (schematically).

CWF32 Fig. 2. Modulation of the amplifier output intensity at 670 nm due to the residual reflection: comparison between of theoretical and experimental results.

In our case, the beam of a 7.8 mW oscillator diode (670 nm) was reduced by an isolator to 5.6 mW and amplified by a double-pass broad-area diode with 100% mirror and AR coating at the front face (total gain 240). A power of >100 mW was extracted and attenuated by spatial filtering to 80 mW. The astigmatism was corrected by cylindrical lenses and tilted curved mirrors (setup in Fig. 1). The beam was coupled into a bow-tie ring resonator of 704 mm length consisting of 4 HR dielectric mirrors. LBO has been used as SHG crystal. A small part of the circulating fundamental wave which was transmitted by one of the mirrors could be injected into the oscillator as feedback signal. The phase was wobbled by a piezo-translator which was driven by a frequency generator with voltage amplifier. A phase control circuit containing a Hansch-Couillaud-type polarization-sensitive detector^{2,3} was used. Different types of spectrally and spatially selective feedback arrangements have been tested, in particular a feedback loop with a double-pass grating and spatial filtering, an external grating resonator for the oscillator and filtering with self-imaging microlens arrays. An input coupling efficiency of 60%, a circulating intensity of 5 W in the ring resonator (enhancement factor >60), a conversion efficiency of $>1.2 \times 10^{-5} \text{ W}^{-1}$ and a UV output power at 335 nm of >275 μW have been achieved. The total losses of the resonator can be estimated to be 1.6%. Stability prob-

CWF32 Fig. 3. Detuning of the amplifier angular characteristics due to internal FP resonances in dependence on the heat sink temperature detected by the measured lateral shift of MOPA far-field distributions.

lems arise from the residual modulation of the diode drivers and from parasitic reflections. Despite the low reflectance of the amplifier face (5×10^{-4}), significant Fabry-Perot interferences were indicated by a modulation of the gain in dependence on temperature, injection current and angular direction. The lateral shift of far field distributions as a function of the heat sink temperature is depicted in Fig. 2. From the spectral modulation of ASE and spontaneous emission of the amplifier, the residual reflectance has been estimated on the basis of the theory of Dai *et al.*⁴ (Fig. 3). The results (calculated gain and residual reflection are higher than theoretical) indicate that additional losses have to be taken into account (diffraction at dynamic gratings).

In principle, enhancement factors of >200 can be achieved by comparable ring resonators.⁵ However, for passive SHG resonator losses <1%, additional losses by frequency conversion influence the system behavior noticeably and can lead to oscillations, beatings and unstable operation (chaos). To reach a more stable operation, a pulsed scheme with mode-locked external laser diode resonator containing the SHG ring resonator as a sub-resonator is proposed.

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CWF33

Harmonic generations in waveguides induced by photorefractive spatial solitons

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Since they have been predicted and observed six years ago, photorefractive spatial solitons have attracted substantial research interest. Apart from several new fundamental aspects related to solitons¹ in general, photorefractive solitons induce optical waveguides which bring about several interesting applications.² One of the unique applications has to do with Second Harmonic Generations³ (SHG) or other parametric processes inside such waveguide structures, in a new highly tunable and highly efficient method. Since most photorefractive media are non-centrosymmetric crystals with large χ^2 nonlinearities, one can use the highly flexible waveguides induced by solitons for highly tunable nonlinear frequency conversion purposes. In this report, we propose a technique utilizing the soliton-induced waveguides to realize SHG with adjustable phase-matched wavelengths.

For SHG, it is always desirable to confine tightly the interacting beams in a waveguide structure because the conversion efficiency increases with the increasing optical intensity and the increasing interacting length. The phase-matching conditions in such waveguides are determined by the propagation constants of the interacting guided modes. One can therefore take the advantage of the fact that the propagation constants of the guided modes in the waveguides induced by photorefractive solitons are tunable by varying the intensity ratio between the soliton peak intensity and the so-called background intensity (the intensity of a uniform beam² that is co-propagating with the soliton) to realize the tunable SHG with no mechanical or temperature movements. The idea is to hold the soliton beam at a fixed direction and position, and vary only its intensity while adjusting the applied voltage, so that one "walks" along the soliton existence curve, that is, the curve that describes all fundamental solitons in parameter space.

Consider a soliton propagating in a photorefractive crystal. The soliton forms a waveguide which can confine the fundamental (of wavelength λ_1) and the second harmonic (of wavelength $\lambda_2 = \lambda_1/2$) beams for SHG. Assuming this waveguide is not affected by both beams, we follow the same steps in Ref. 2 to calculate the propagation constants of them

CWF33 Fig. 1. Effective indices of the interacting beams, $n_{eff1,2}$, as functions of the intensity ratio for waveguides induced by (a) bright [with $\lambda_1 = 982.5$ nm] and (b) dark [with $\lambda_1 = 1000$ nm] solitons.

CWF33 Fig. 2. Phase-matched wavelengths (shown by λ_1) as functions of intensity ratios, for waveguides induced by (a) bright or (b) dark solitons.

CWF33 Fig. 3. Inverse of the effective interacting width, R^{-1} , as functions of intensity ratios, for waveguides induced by (a) bright or (b) dark solitons.

at different soliton intensity ratios. We represent the propagation constants $\beta_{1,2}$ of the fundamental and the second harmonic by their effective refractive indices, $n_{eff1,2} = \beta_{1,2} \cdot \lambda_{1,2} / (2\pi)$. The phase-matching condition therefore becomes $n_{eff1} = n_{eff2}$. Before the soliton-induced waveguide forms, [unless some specific crystalline orientation is chosen to start with] $n_1 \neq n_2$ in general (phase not matched). When the soliton forms, the effective refractive indices $n_{eff1,2}$ deviate from $n_{1,2}$ by a value proportional (with different proportional constants) to the normalized propagation constants,² which are functions of the soliton intensity ratio. "Walking" on the soliton existence curve by tuning intensity ratio, we derive two curves of n_{eff1} and n_{eff2} as functions of this ratio. At the specific intensity ratio where $n_{eff1} = n_{eff2}$, this set of the fundamental and the second harmonic becomes phase-matched, and the curves of n_{eff1} and n_{eff2} intersect, as shown in Fig. 1.

Figure 2 shows the phase-matched wave-

lengths induced by bright or dark solitons. These examples are calculated in a normal incident b-cut $KNbO_3$ crystal under the following conditions. The solitons are of wavelength $\lambda = 488$ nm, polarized along c-axis and with soliton size 5 μm FWHM, the fundamental beams for SHG are polarized along a-axis, and the second harmonic are polarized along c-axis. It shows that the tuning range for the waveguides induced by bright solitons is about 5 nm while the tuning range by the dark solitons can be more than 40 nm. This is because the propagation constants of the guided mode in dark-soliton-induced waveguides² can vary in a greater amount. Other than the phase-matching condition, the overlap integral between the fundamental and the second harmonic is also an important factor affecting the conversion efficiency. The overlap integral can be represented by the inverse, R^{-1} , of the effective overlap width (the smaller the better). Figure 3 shows R^{-1} for bright and dark-soliton-induced waveguides. Again, the dark soliton shows its advantage by giving more than 50 times of efficiency compared to the bright soli-

ton. However, even the bright soliton yields an overlap integral that is comparable to a fabricated waveguide⁴ of the same size.

For experimental realization, suitable doping and well separated wavelength (PR effect is wavelength-dependent) between the interacting beams and the soliton are necessary to prevent the generated second harmonic wave from being absorbed by the PR material. On the other hand, one can think of an "active design", in which the second harmonic is photosensitive to the PR material; we do not even have to launch the soliton beam in the bright soliton case. The generated second harmonic can act as the bright soliton beam building the waveguide at the expense of part of its intensity. Notice that this technique can also be applied to other parametric processes, too, with an advantage that the frequency tuning can be done without any mechanical or temperature movement.

An effort to experimentally demonstrate tunable SHG in soliton induced waveguides is carried out in our laboratory at this moment, with $KNbO_3$ and at Ti:sapphire wavelength.

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Generation of 220 fs, 351 nm pulse by high yield efficient frequency tripling of 1.06 μm , chirped pulses

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The generation of ultrashort pulses has been progressing in the recent years with outstanding advances in the shortening of pulses and the increase of their spectral regions of emission.¹ However, the extension to the UV-wavelength region appears difficult, particularly if energy is sought. This is due to the lack of direct laser broadband UV sources with high saturation fluence, or to bandwidth limitation in the frequency conversion process. This latter limitation is particularly drastic in the case of third harmonic generation.

We previously reported a concept² and his preliminary experimental verification which allows to efficiently frequency triple broadband pulses using an adapted chirped pulse amplification (CPA) configuration. The idea is based on the manipulation of pulses with appropriate chirps for maintaining phase match-