COMPACT VIOLET LASERS BY SECOND-HARMONIC GENERATION IN KTP WAVEGUIDES

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Abstract

Periodically segmented waveguides were fabricated in flux-grown KTP for quasi-phasematched second-harmonic generation (SHG) of a light beam with a wavelength of 425 nm. Diode-pumped violet laser sources are proposed on the basis of these waveguides. We shall show that a pulsed operation of the pump diode laser at a 940 MHz repetition rate enables the construction of sources with a very compact geometry, which are insensitive to temperature fluctuations. These sources may still be considered as quasi-continuous wave (cw) for applications in high-density optical recording.

The most compact type of violet laser source has a size of 1 x 1 x 2 cm³. It contains only the diode pump laser, the KTP waveguide and a miniature lens to couple the pump beam to the waveguide. Time-averaged violet output powers up to 85 μW have been generated for many hours at room temperature without requiring an active temperature control. This output power may be sufficient for reading an optical disc.

By optical feedback of a portion of the transmitted pump beam via an external grating it is possible to generate higher violet powers. In this way, the pump laser is forced to operate in a single spectral mode, the wavelength of which can be tuned to coincide with the phase-matching wavelength of the waveguide. This grating-controlled laser system is shown to generate a 425 nm beam with powers up to 0.5 mW. The total length of the device is about 7 cm.

Keywords: blue/violet laser, non-linear optics, optical recording, second-harmonic generation, waveguiding, pulsed laser.

1. Introduction

Frequency doubling of an infra-red pump beam in an optically non-linear material is one of the possible options for the generation of a blue/violet beam [1] for application in high-density optical recording [2]. High-power AlGaAs lasers can be used as pump sources in the 780–860 nm wavelength
region, enabling the construction of compact violet laser devices. A high optical pump density is required in order to obtain a large conversion efficiency. Tight focusing of the pump beam in the non-linear material is therefore essential. An effective way of satisfying this condition is to confine the pump beam in an optical waveguide made in a suitable non-linear optical substrate crystal such as KTP [3, 4].

Efficient conversion in the above wavelength region has been found after the channel waveguide is replaced by one with a periodically segmented domain-inverted structure in KTP [5, 6]. At Philips Research we have been successful in fabricating such periodically segmented waveguide converters [7–9]. We have made Rb/Ba diffused waveguides in KTP with an exchange process that is similar to that described in ref. [5].

Risk et al. [10] have successfully used periodically segmented KTP waveguides to construct diode-pumped violet laser sources. They maximized the efficiency of the devices by improving on the coupling efficiency of the diode pump beam to the waveguide. This was done by introducing a system of beam-circularizing optics. In this paper, I describe the construction of similar violet laser sources. I have aimed, however, to make them as compact and stable as possible, if necessary at the expense of absolute SH output power. The most compact device geometry consists of a high-power pump diode laser, a miniature coupling lens and the frequency-doubling KTP waveguide. One remaining problem is, however, the matching of the laser wavelength to the phase-matching wavelength of the waveguide. Liedenbaum has found a solution to this problem in which the pump diode laser is driven by a radio-frequency source [11]. At a frequency of 940 MHz the laser is found to produce 400-ps optical pulses. The spectrum of the pulsed laser appears to be multi-mode over an extensive wavelength region of about 10 nm in width. This makes it much simpler to obtain an overlap with the narrow acceptance band for phase-matched SHG. Obviously, the multi-mode laser spectrum leads to a significant decrease in pump-to-SH conversion efficiency since the large majority of the laser power is produced outside the phase-matching spectrum. In practice, however, the mixing of pump photons from two modes that are both outside the acceptance bandwidth will also contribute to the generation of violet light. I will show that the remaining output power can still be made high enough for potential application in read-only optical recording. The pulse rate is high enough to consider the source as (quasi-)cw in this application.

Higher violet output powers can be obtained by forcing the laser to operate in a single spectral mode by feedback coupling of the pump beam via an external grating [10, 12]. A maximum SH output power is obtained by tuning the laser
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wavelength with the grating to coincide with the phase-matching wavelength of the waveguide. In this paper, I will extend this technique to include pulsed operation of the pump laser source.

In Sec. 2, I give a brief description of SHG in KTP waveguides and some experimental results. Sec. 3 contains descriptions of compact violet laser sources based on these KTP waveguides. Finally, conclusions are given in Sec. 4.

2. SHG in periodically segmented waveguides in KTP

The normalized pump-to-SH conversion efficiency $\eta$ for SHG is defined as

$$\eta = \frac{P_{2\omega}}{(P_{\omega}L^2)}$$

and is expressed in $\% W^{-1}cm^{-2}$. $P_{2\omega}$ and $P_{\omega}$ are the total SH and pump power in the waveguide, respectively, and $L$ is the guide length. For a periodically segmented waveguide with a perfectly uniform segmentation structure, $\eta$ is given by [7, 13]

$$\eta = \eta_{\text{max}} \text{sinc}^2 \left( \frac{2.78(\lambda - \lambda_0)}{\Delta \lambda_{1/2}} \right)$$

where $\eta_{\text{max}}$ is the conversion efficiency for SHG at the phase-matching wavelength $\lambda_0$. The wavelength of the pump laser is $\lambda$. $\Delta \lambda_{1/2}$ is the full width at half maximum of the phase-matching spectrum $\eta(\lambda)$. For KTP, the value of $\Delta \lambda_{1/2}$ is given in ref. 7 as a function of the segmentation period length $\Lambda$.

In waveguides with a non-uniformity in the segmentation structure the phase-matching spectrum is broadened with respect to the spectrum in eq. 2. Furthermore, the shape usually deviates significantly from the $\text{sinc}^2$ shape. Therefore, we introduce $\eta_i$ as the efficiency of conversion after integration over the pump wavelength. For a uniform waveguide we obtain from eq. 2:

$$\eta_i = L \int_{-\infty}^{\infty} \eta d\lambda = 1.1(\Delta \lambda_{1/2}L)\eta_{\text{max}}$$

By definition, $\eta_i$ is independent of the guide length, and is expressed in $\% W^{-1}cm^{-1}nm$. We will show elsewhere that, for practical KTP waveguides with some non-uniformity in the segmentation structure, $\eta_i$ is approximately independent of line broadening. If a pump laser is used with a multi-mode spectrum, the spectral width of which is larger than that of the phase-matching spectrum, we derive in the Appendix that the conversion efficiency is dependent on $\eta_i$ and not on the shape of $\eta(\lambda)$. The conversion efficiency is therefore insensitive to the broadening of the phase-matching spectrum. The tolerances on the uniformity of the segmentation structure are therefore less critical for a multi-mode pump laser than for a laser with a single spectral line.
Periodically segmented waveguides were fabricated on c-cut flux-grown KTP substrates from the Philips Research Laboratories in Briarcliff Manor (NY) [14]. The fabrication process has been described previously in refs. [5, 7, 9]. To summarize, a Ti-masking layer is deposited on the KTP substrate and structured by a photolithographic process. The exchange process is performed in a melt bath consisting of a mixture of RbNO₃ and BaNO₃ at a temperature between 300 and 400°C. After exchange, the Ti layer is removed. We use a wavelength-tunable (cw) Ti-sapphire laser for the characterization of the SHG properties of the waveguides [9]. The waveguide samples are not anti-reflection coated, so that a Fresnel reflection loss of 9% occurs at both coupling facets of the guide.

In Fig. 1 we give measured conversion spectra for some fabricated 4 μm period Rb/Ba diffused waveguides. The depth and width of the waveguide segments were about 4 μm. The measured peaks correspond to conversions between guided pump and SH beams that both have fundamental mode inten-
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Fig. 2. Geometry of a compact violet laser. a) gives the schematic layout and b) shows the practical realization.

Intensity distributions. The spectra in Figs. 1a) and 1c) show a single peak, whereas the spectrum of Fig. 1b) is broadened, probably by non-uniformities in the segmentation structure of that waveguide. For the same reason, the peak efficiency is considerably lower than that of the other waveguides. The integrated efficiency of this waveguide is, however, about 35% W$^{-1}$cm$^{-1}$nm, which is larger than the value of 25% W$^{-1}$cm$^{-1}$nm measured for the other waveguides. This
waveguide is therefore expected to lead to a higher efficiency for SHG with a multispectral mode pump laser than the other two, whereas for a single-mode pump laser the other two will be optimum choices. This will be shown in Section 3.

3. Development of compact violet laser sources

3.1. Low-power version

The central part of a highly compact violet laser source consists of a high-power AlGaAs diode laser (operating at about 850 nm wavelength), a KTP waveguide, and a miniature lens which couples the pump beam efficiently into the waveguide. In Fig. 2, we show a practical geometry for such a violet laser source. The dimensions of the device are approximately 1 x 1 x 2 cm³.

The AlGaAs pump lasers were specially grown for this application at the Philips Opto-electronic Centre (POC). Their active region consists of two GaAs QWs each 8 nm thick. The laser front and back facets were coated with 2.5% and 88% reflective coatings, respectively. The thickness of the step-index optical confinement region and the width of the etched mesa were adjusted to obtain a single spatial-mode laser beam with transverse and lateral widths of 33 and 11°, respectively. This design was an optimum compromise for obtaining an efficient beam coupling to KTP waveguides through a miniature lens with an NA of 0.3 without leading to very high values for the laser threshold current. Some of the lasers were soldered with the epitaxial layers facing down on the cooling mount (epi-down); others were mounted with the substrate side down (epi-up) in order to obtain a longer wavelength.

Continuous-wave output powers to well over 100 mW were generated by both types of laser, as is shown in Fig. 3a). The efficiency and maximum output power of the epi-up mounted lasers is lower because of the less efficient cooling of the laser active region by the mount. In Fig. 3b) we show the measured laser wavelength as a function of output power. Well above threshold, the lasers operate in one dominant spectral mode, usually however with a number of smaller modes still present. At their maximum output power levels, the laser wavelength is approximately equal to the phase-matching wavelengths of the 4 µm period Rb/Ba diffused waveguides in KTP (see Fig. 1).

An improvement in pump-to-SH conversion efficiency is expected for pulsed operation of the pump laser at a given value of the average pump power. However, the pulse rate should be chosen significantly higher than 100 MHz for the violet laser source to be considered as quasi-cw for many applications such as optical recording. The 900 MHz frequency region is used in wireless telephone
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Fig. 3. Characteristics of GaAs–DQW pump lasers at 25°C. a) shows the cw output power as a function of the dc current for two sets of lasers (see text). The broken curve gives the average output power for pulsed operation at 940 MHz. b) shows the laser wavelength as a function of output power for cw operation.
communication systems. Standard electrical components are therefore available for building a compact 300 mW rf power source at a frequency of 940 MHz. The rf current is mixed with that of a dc current source in a bias-T, and fed to the laser. In Fig. 3a) we show the average laser power of the epi-down mounted lasers at pulsed operation as a function of the dc part of the laser current. As a result of the rf current contribution, the dc part of the laser threshold current is 0.43 times that found for cw operation of the same laser. The slope of the L–I curve is smaller than in the case of cw operation, and the curves cross at an output power of about 110 mW. At higher dc current, gain saturation will cause the average output power to be lower for pulsed operation than for cw operation. The optical pulse length is found to increase from about 250 ps at 50 mA to 370 ps at 170 mA. Therefore, the maximum peak power of the laser is about 350 mW. The spectrum of the free-running laser consists of many longitudinal cavity modes. The full width of the envelope function to this spectrum is found to increase from 8 nm at a bias current of 50 mA to 13 nm at 170 mA. The ‘centre-of-gravity’ wavelength at a given average power value is found to be between 0.5 and 1.0 nm longer than that given in Fig. 3b) for cw operation.

In Fig. 4 we present the transmitted pump power measured at the end of a 4.5 mm long Rb/Ba waveguide as a function of the magnification factor of the coupling lens. This power has been normalized to that of the laser. The measurements were performed after optimizing the lateral and transverse positions of the waveguide with respect to the incoming beam. This required a position tolerance better than 0.2 μm. A maximum pump-beam transmission of 37% is found at a lens magnification factor of 2.1. We find 48% maximum transmission if we correct for the loss introduced by the limited NA of the coupling lens. This is shown in the broken curve. By neglecting the internal absorption and scattering losses in the guide and the Fresnel reflections at the guide facets, we predict a total transmission value of 53% from model calculations for this geometry. Comparing this with the experimental result, we conclude that the contribution of internal and Fresnel losses is about 30% for this guide. This indicates that, by a complete optimization of the beam coupling geometry, the pump power in the guide might be further improved by a factor of two, and consequently the SH power by a factor of four. In practice, this would, for example, be possible by adding beam-correcting optics in a combination with a $\frac{1}{2} \lambda$ plate [10]. However, this also leads to a less compact and more complicated device, so we decided to accept the loss of a factor of four in SH power for the present devices.

The above-mentioned measurements were performed in cw operation at a low value of the laser current. In Fig. 5a) we show what happens when we increase the laser current and the corresponding output power of the laser.
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Fig. 4. Measured efficiency for coupling a diode laser beam to a 3 \( \mu \text{m} \) deep, 4 \( \mu \text{m} \) wide and 4.5 mm long Rb/Ba diffused KTP waveguide as a function of the coupling lens magnification factor. The solid curve gives the pump power collected at the exit facet of the waveguide relative to the total emitted power of the laser diode. The broken curve gives the transmission factor after correction for the transmission of the coupling lens.

We have plotted the transmitted power through the waveguide, \( P_w \), as a function of the laser current. The transmitted laser power is found to depend heavily on the laser current in the region above 50 mA. The transmission suffers from abrupt changes by a factor of about two. We then used a monochromator to check on the wavelength of the laser beam at the various currents. These values are indicated in the Figure. The sharp transitions in the beam transmission are found to correspond with large changes in the wavelength of the diode laser. In fact, there are two limiting transmission characteristics, both indicated by dotted curves in the Figure. The ‘high transmission’ curve corresponds to a laser wavelength of about 852 nm, whereas the laser wavelength was 865 nm for the ‘low transmission’ curve.

The explanation of this phenomenon is found in the transmission properties of the waveguide in this wavelength region, which are shown in Fig. 5b). A narrow dip is found in the transmission spectrum at a wavelength of about 865 nm. This dip corresponds with the 17th-order Bragg reflection at the 4 \( \mu \text{m} \) periodically segmented structure of the waveguide [15]. For increasing values of the laser current the gain spectrum of the laser becomes broader and gradually extends towards the 865 nm wavelength. If then a cavity-mode wavelength of the laser coincides with the wavelength of this Bragg reflection
Fig. 5. Transmission of the KTP waveguide of Fig. 4 for various pump laser conditions. a) shows the power of the transmitted laser beam, $P_\omega$, as a function of the laser current (cw operation). The broken curve gives the power of the incident laser beam $P_\text{in}$ measured after the coupling lens. The operating wavelength of the laser in several regions of the laser current is indicated. b) shows a part of the transmission spectrum of the waveguide near the 17th-order Bragg reflection.
peak, the laser wavelength hops to this mode. This situation occurs within a number of distinct regions in the laser current. Outside these regions, the wavelength overlap is reduced and the locking of the laser wavelength to the Bragg peak is lost. The laser returns to its original wavelength.

At currents above 100 mA, the laser starts operating at cavity modes both at 854 nm and at 865 nm. The measured decrease in transmission in Fig. 5a) is in good agreement with the measured Bragg transmission spectrum in Fig. 5b). Although an SH output power was measured in particular current regions (the phase-matching wavelength of the guide was 852.5 nm), it is clear that this type of cw operation of the diode laser does not lead to a stable generation of an SH beam. Bierlein [16] has proposed that the periodic structure of the waveguide be adapted to obtain a coincidence between the phase-matching wavelength and a Bragg reflection peak of the waveguide. Although this approach was reported to work, it is clear that this condition depends rather critically on the waveguide temperature.

Because of the above-mentioned problems, we decided to operate the diode laser under pulsed conditions. Experiments showed that in this case no locking of the laser wavelength to the Bragg reflection peak occurred for dc bias currents up to 200 mA. Obviously, the spectral multi-mode character of the pump laser leads to a decrease in conversion efficiency, since only a few of these modes are phase-matched for efficient SHG. In practice, however, the loss in efficiency is less severe than might be expected, which is due to a large contribution of upconversion mixing between different laser modes [17] (see Appendix).

In Fig. 6a) we show a compact low-power violet laser source in operation. The device produces an almost circular violet output beam with a full angular width of about 9°. Relatively small contributions are visible from the scattering of the generated SH beam at the periodic structure of the waveguide. The single-lobed shape of the main output beam is caused by the fact that phase-matching predominantly occurs in the fundamental mode SH beam confined in the waveguide.

In Fig. 7a) we present the operating characteristics of two violet laser devices constructed from 4.5 mm long KTP waveguides with 851.9 nm phase-matching wavelength (see Fig. 1c). The measurements were done at room temperature without any active control of the device temperature. With the epi-up mounted pump diode laser, average SH output powers of up to 30 \( \mu \text{W} \) are generated at a dc bias current of 130 mA. The rf source was operated at a fixed power of 300 mW. The transmitted pump power is indicated in the Figure as a reference. A steep decrease in SH output power is found at currents higher than 130 mA, despite the increase in guided pump power. This is caused by the fact that the central laser wavelength of the laser becomes larger than the phase-matching wavelengths.
Fig. 6. Pulsed violet laser systems in operation. a) shows the compact low-power version of a violet laser source. b) shows a test version of a high-power violet laser system with external grating control.
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Fig. 7. Performance of compact pulsed violet laser devices. The measured average 425 nm output power is shown as a function of the dc bias current through the pump diode laser. The rf current source was operated at standard conditions. a) shows results for 4.5 mm long waveguides and b) for 7.5 mm long waveguides. Pump lasers were used which were mounted with the epitaxial layers or the substrate side facing the cooling mount (epi-down or epi-up, respectively). The dashed curves give the average pump power measured at the exit facet of the waveguide.
wavelength in that region of current. This leads to a decrease in conversion efficiency. For the epi-down mounted laser the maximum SH output power is only 26 $\mu$W, which is obtained at a larger current and correspondingly higher pump power. The measured lower conversion efficiency is caused by the fact that, for this laser, the centre laser wavelength remains lower than the phase-matching wavelength over the whole current range.

In Fig. 7b) we show the measured results for 7.5 mm long waveguides with a lower phase-matching wavelength of 849.9 nm (see Fig. 1b): This wavelength is a better match to that of the epi-down laser. SH output powers of up to 85 $\mu$W were obtained. For the epi-up mounted laser, the maximum SH power of 50 $\mu$W is obtained at about 100 mA dc bias current, which is a lower current value than for the above 4.5 mm long waveguides.

These experimental results show that, despite a difference in wavelength of about 4 nm, both types of laser lead to similar SH output powers in a given waveguide. This indicates that the sensitivity to changes in the laser temperature is also relatively small. The temperature bandwidth for operation of the above compact violet laser sources is therefore about 15°C, which is extremely large for SH converters. Although we have not performed extensive life tests yet, the above power levels could indeed be maintained for many hours without any active temperature control.

We can now compare the measured pump-to-SH conversion efficiencies for these pulsed devices with estimated efficiencies obtained on the basis of the characteristics of the waveguides and pump lasers. In the Appendix we show that the time-averaged conversion efficiency $\bar{\eta}_m$ of a pulsed multi-mode diode-laser beam in a frequency-doubling waveguide is given by

$$\bar{\eta}_m = 2 \frac{\eta_i \Delta t_{\text{rep}}}{\Delta \lambda_{\text{las}}} \frac{t_p}{t_{\text{rep}}}$$  \hspace{1cm} (4)$$

where $\eta_i$ is the integrated conversion efficiency of the waveguide measured with the cw Ti–sapphire laser, $\Delta \lambda_{\text{las}}$ is the full width of the envelope of the multi-mode spectrum of the diode laser, $t_p$ is the pulse time and $t_{\text{rep}}$ is the time between pulses. We have assumed that the 'centre' wavelength of the laser coincides with the centre of the acceptance band.

For the 4.5 mm and 7.5 mm long waveguides, we have obtained $\eta_i = 25$ and 35% W$^{-1}$cm$^{-1}$nm from the spectra of Figs. 1b) and 1c), respectively. After insertion of these values in eq. 4, and by using experimental values for $\Delta \lambda_{\text{las}}$ and $t_{\text{rep}}/t_p$, we obtain $\bar{\eta}_m \approx 15\%$ W$^{-1}$cm$^{-1}$ for both types of waveguide. From the measured SH and pump output powers of the violet laser devices in Fig. 7, we obtain an experimental value of $\bar{\eta}_m \approx 17\%$ W$^{-1}$cm$^{-1}$, which is in good agreement with the predicted value. The measured efficiency of the devices is
therefore close to the optimum to be expected for the present KTP waveguides and AlGaAs diode lasers. Furthermore, this result shows that the broadening of the phase-matching spectrum of the 7.5 mm long waveguides (see Fig. 1b) has not affected the conversion efficiency of the pulsed devices made with these waveguides. This places less stringent demands on the uniformity of the segmentation structure and therefore on the fabrication process of KTP waveguides for these devices.

Although we have not yet performed direct tests with these violet laser devices, we expect that the power level of the output beam is high enough for application in read-only optical recording. The signal-to-noise level of the devices is measured to be 63 dB (10 kHz bandwidth at 500 kHz). The frequency-doubling process must therefore introduce an additional 20 dB noise to the −83 dB noise level of the pump laser. This is probably the result of the multi-spectral-mode operation of the pump laser.

### 3.2. High-power version

In the previous section, we have shown a very compact SH laser device that produced a stable violet output beam at, however, a relatively low power level. An increase in output power is expected if the laser is to operate in a single spectral mode and if the wavelength of this laser coincides with the wavelength acceptance band for phase-matched SH generation. This can be done by feedback of the pump beam to the diode laser after first-order diffraction at an external grating [10, 12]. In this section, we apply this principle to obtain a high-power version of a pulsed violet laser system.

A practical geometry for a grating-controlled violet laser system is shown in Fig. 8a). The miniature pulsed system of Sec. 3.1 has been extended to include a standard NA = 0.25 objective lens, which collimates the pump and SH output beams from the waveguide into parallel beams. A glass beam-folding block with wavelength selective coatings (high reflection at 850 nm) is used to separate the SH and pump beams. The transmission of the multilayer coating at the SH wavelength is 0.64. The pump beam follows a folded path to arrive at a 600 lines/mm grating. There, the beam is diffracted in first order at the grating and sent back to the laser. By this feedback signal, the laser is forced to operate in a single spectral mode. The tilt angle of the grating is adjusted such that the laser wavelength is made to coincide with the phase-matching wavelength of the waveguide, which results in an optimum generated SH power.

For the present pulsed system, the use of the beam folding block is essential in order to obtain a compact geometry. The spatial length of a 300 ps optical pulse is only about 10 cm. Therefore, the external grating cannot be placed close
Fig. 8. Pulsed violet laser system with external grating control. a) shows schematically the geometry of the device; b) shows the performance of the test set-up shown in Fig. 6b). The measured time-averaged 424 nm output power is given as a function of the dc bias current through the pump diode laser. The rf source was operated under standard conditions.

enough to the laser to provide an effective feedback of each laser pulse to itself. The feedback therefore has to occur between subsequent pulses. The external grating must therefore be placed at an optical distance from the laser that is equal to half the spatial distance between laser pulses. This distance between two laser pulses at 940 MHz repetition frequency is 32 cm in vacuum. The minimum optical distance between the laser and the grating should therefore be 16 cm. Without the folding block, this would lead to an unacceptably long device. With the block, the total length of the device is made less than 70 mm.

In Fig. 6b) we show a complete test system in operation. In this case, we have not used the compact violet laser system of the last section as a basis. Instead, we
have chosen to build the system with distinct components in order to test the influence of their relative positions on the SH output power. For these experiments we have used the 7.5 mm long KTP waveguide, the phase-matching spectrum of which has been shown in Fig. 1a).

In Fig. 8b) we present the measured average SH output power of the system as a function of the dc bias current through the pump laser. The rf source was operated under standard conditions (see Sec. 3.1). No attempts were made to actively stabilize the temperature of the components. During the scan of the laser current, the relative positions of all components (including the grating) were not adjusted. The output vs. bias current curve shows an oscillatory behaviour, with a maximum SH output power of about 500 $\mu$W at 170 mA. By measuring the spectrum of the diode laser during the scan, we found that the oscillations are caused by a current-induced shift in the wavelength position of the longitudinal cavity modes of the laser. This causes the laser wavelength to be tuned as a function of current through the peak region of the phase-matching spectrum of the waveguide. When the size of the wavelength shift approaches that of the distance between two cavity modes, the grating forces the laser to hop to the next cavity mode. Such behaviour might be avoided by applying a better anti-reflection coating to the front facet of the laser. This does, however, have some disadvantages in the alignment procedure of the system, as then laser action can be obtained only after the feedback has been established.

After correcting for the SH transmissions of the collimating lens and the coating on the beam-folding block, we derive that a maximum time-averaged SH output power of about 1 mW is produced by the waveguide at 170 mA dc bias current. The corresponding pump power levels measured at the laser facet and after the waveguide were 110 mW and 35 mW, respectively. The conversion efficiency of the waveguide for pulsed operation is therefore 80% W$^{-1}$. At 50 mA dc bias current, the efficiency is however found to be about 180% W$^{-1}$. Part of the decrease in efficiency at higher laser currents is attributed to the increase in the pulse length of the pump laser. After correcting for the pulsed operation, we find that the conversion efficiency is about 35% W$^{-1}$. This is a factor of 3 lower than the 110% W$^{-1}$ peak efficiency that we have measured with the Ti:sapphire laser in this waveguide (see Fig. 1a). A similar discrepancy in efficiency has been reported by Risk et al. [10] for a cw extended-cavity SH laser. They ascribe this discrepancy to the different spectral characteristics of the Ti:sapphire laser as compared with those of the extended cavity diode laser (see also the Appendix).

The generated SH output power depends on the optical distance between the laser and the external grating. This is illustrated in Fig. 9 for the case of the 4.5 mm long waveguide, the phase-matching spectrum of which is shown in
Fig. 1c). For this measurement, the external unit consisting of the beam-folding block and the grating was scanned around an axial position that was 160 mm further away from the waveguide exit facet than in the previous experiments. For $\Delta z > 0$, a sharp decrease in output power is found. Apparently, the optical pulse that is diffracted at the grating is now returning too late at the laser to force the laser to start up at the grating controlled wavelength. The feedback control is lost completely and the laser operates in the multi-mode spectrum as described in Sec. 3.1. When the grating unit is placed too close to the laser, the decrease in SH power is less abrupt. Here, the feedback is given by the tail of the optical pulse that returns from the grating. Optimum SH powers are obtained within a $\Delta z$ region of about 3 mm, which corresponds to a time delay range of 20 ps. This seems to be not too critical for a practical realization of the grating-controlled pulsed violet laser system.

Fig. 9. Influence of the relative axial position of the grating on the performance of a grating-controlled pulsed violet laser system. The measurements were performed with a 4.5 mm long KTP waveguide and with the pump laser operated at a dc bias current of 135 mA and standard rf conditions.
4. Conclusions

Pulsed operation of the pump diode laser is found to enable the construction of a very compact and stable violet laser source. This is a result of the multi-mode spectrum of such a pulsed laser. At first, the multi-mode operation was expected to lead to a dramatic decrease in conversion efficiency because most of the cavity modes are not within the phase-matching bandwidth for SHG. In practice, however, all cavity modes are found to be generated in the laser simultaneously. Up-conversion mixing between these modes turns out to be the primary source for the generation of violet output power. The loss in efficiency is therefore less than expected at first sight and the resulting power level is probably still sufficiently high for the reading of information from an optical disc. An additional benefit of this mode of operation is that the efficiency is relatively insensitive to variations in the ambient temperature and laser current.

Higher SH output powers are obtained by extending the above device to include an external grating via which a wavelength-dependent feedback is introduced to the diode laser. This forces the laser to operate in a single-spectral mode, the wavelength of which can be tuned to coincide with the phase-matching wavelength of the KTP waveguide. We have shown that such a system can still be made fairly compact. Furthermore, it has been operated for an extensive period without the need for active stabilization of the laser and waveguide temperatures. After further optimization of the SH transmission of the collimating lens and of the dichroic mirror on the beam folding block, the generation of mW violet output power is possible with this compact system.

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The conversion efficiency of the SH process for the case of a multi-mode pump laser is given by

\[ \eta = \eta_{\text{max}}^{\text{SH}} \frac{2 \sum_{ij} (E_i E_j S_{ij})^2 - \sum_{j} (E_j^2 S_{jj})^2}{\left( \sum_{j} E_j^2 \right)^2} \]  

(A1)

where \( \eta_{\text{max}}^{\text{SH}} \) is the conversion efficiency for SHG with a single-mode pump laser with its wavelength at the phase-matching wavelength \( \lambda_0 \). \( E_i \) is the electric pump field of laser mode \( i \). \( S_{ij} \) represents the phase-matching acceptance band and is a function of the mismatch in the wavelength \( \Delta \lambda_{ij} \) given by

\[ \Delta \lambda_{ij} = (\lambda_i + \lambda_j)/2 - \lambda_0 \]  

(A2)

Equation A1 includes the contribution of the up-conversion process by the mixing of photons from different cavity modes in the pump spectrum. If the total width \( \Delta \lambda_{\text{las}} \) of the multi-mode laser spectrum is smaller than the bandwidth \( \Delta \lambda_{1/2} \) for phase-matching, we obtain from eq. A1

\[ \eta_{\text{max}} = \eta_{\text{max}}^{\text{SH}} (2 - 1/N) \approx 2 \eta_{\text{max}}^{\text{SH}} \]  

(A3)
where we have assumed that the laser spectrum consists of a large number of modes.

This situation exists in the case of the Ti–sapphire laser that we have used to evaluate the SH characteristics of the KTP waveguides. If we assume that the multi-mode laser spectrum is much broader than the phase-matching spectrum and that these spectra perfectly overlap, we obtain from eq. A1

$$\eta = 1.1 \times \eta_{\text{max}}^{\text{SH}} \left( 4 \frac{\Delta \lambda_{1/2}}{\Delta \lambda_{\text{las}}} - \frac{1}{N} \frac{\Delta \lambda_{1/2}}{\Delta \lambda_{\text{las}}} \right) \approx 4.4 \times \eta_{\text{max}}^{\text{SH}} \frac{\Delta \lambda_{1/2}}{\Delta \lambda_{\text{las}}}$$  (A4)

The first term on the right-hand side of this equation describes the contribution from mode-mixing, while the second term gives the contribution, from the SH process, of individual laser modes. If a large number of modes is present in the laser spectrum, the latter contribution is negligible, which leads to the second part of the equation.

We can apply eq. A4 to the case of the broad multi-mode spectrum of a pulsed diode laser with pulse length $t_p$ and pulse repetition time $t_{\text{rep}}$ to derive the time-averaged conversion efficiency given by

$$\bar{\eta}_m = \frac{2 \eta_i t_p}{\Delta \lambda_{\text{las}} t_{\text{rep}}}$$  (A5)

where $\eta_i$ is the integrated conversion efficiency defined in eq. 3. In the derivation of eq. A5 we have assumed that $\eta_i$ is measured with the multi-mode Ti-sapphire laser.

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