A stable high-power waveguide resonator second harmonic device with external conversion efficiency of 75%.

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February 14, 2017

Abstract

We report on a highly efficient waveguide resonator device for the production of 775 nm light using a titanium indiffused LiNbO₃ waveguide resonator. The device stably produces up to 110 mW of second harmonic power with 140 mW incident on the device - an external conversion efficiency of 75%. The cavity length is also locked, using a Pound-Drever-Hall type locking scheme, via one of two methods involving feedback to either the cavity temperature or the laser frequency. Both locking schemes result in a stable output power of at least 10 mW over one hour.

1 Introduction

Integrated optical waveguide technologies offer improvements in size, scalability, integrability and non-linear interaction strength over their bulk counterparts. These properties have been used to create a myriad of impressive devices, such as high-speed switches [1], optical parametric oscillators [2] and frequency conversion devices [3]. Frequency conversion is often used to produce laser fields at wavelengths inaccessible to current materials [4], but can also be used to interface individual parts of a network [3] or to transfer information from one field to another at a different wavelength [5].

Traditionally, the main advantage of waveguide devices has been very high nonlinear interaction strengths, allowing for relatively high conversion efficiencies at low input and low output powers. However, for many applications both high conversion efficiency and high output powers are desired. This is where the performance of waveguides has traditionally been limited, due to a number of factors such as large waveguide losses, poor mode shape profile and high power effects such as photorefraction. Only recently have large improvements in stable, high conversion efficiency and high output power waveguides been realised. The most common architecture used to this aim is MgO:LiNbO₃ ridge waveguides [6, 4, 7, 8]. In contrast to other architectures, the ridge waveguide design allows for magnesium oxide doping, which significantly reduces the photorefractive effect [9, 10]. For example Sun et al have recently produced single-pass waveguides with internal second harmonic conversion efficiencies of around 70% and with output powers exceeding 400 mW at 466 nm [6].

One can further enhance the strength of the nonlinear interaction by resonating the optical field within the waveguide. This method of enhancement has been demonstrated by various groups in a number of different architectures [11, 12, 13, 14, 15]. Resonators also allow one to shape the spectrum of the output light and to tailor the system for optimum conversion for a given pump power and waveguide loss [12]. Despite these benefits investigation of waveguide resonators for high power and high conversion efficiency applications has not been experimentally realised. This is likely due to increased sensitivity to temperature fluctuations and waveguide losses. However, waveguide losses less than 0.1 dB/cm in both
tiitium indiffused and ridge waveguides have been demonstrated in lithium niobate \([11, 16]\). This opens up the possibility of producing high performance waveguide resonators.

In this paper we present the realisation of a high power waveguide resonator, whose external second harmonic conversion efficiency (defined here as the amount of second harmonic power exiting the device divided by the amount of fundamental power incident on the device) of 75\% is, to the best of our knowledge, the highest achieved from an integrated device. The device stably produces up to 110 mW of SH power, after which the output power begins to fluctuate in time, possibly due to photorefraction. The cavity length has also been locked using a Pound-Drever-Hall (PDH) type locking scheme \([17]\), stabilising the output power over many hours. Whilst the wavelength of the converted light is easily accessible by various laser technologies, this device provides access to a phase congruent fundamental (which lies in the communications band) and second harmonic field. This is useful, for example, in nonlinear optics experiments that pump any process with the second harmonic of the field such as parametric amplification and oscillation \([2]\), as well as detection of these states using, for example, balanced homodyne detection \([18, 19]\).

2 The waveguide SHG device

The performance of the waveguide SHG resonator will depend on many factors such as loss, nonlinear strength, photothermal properties, photorefraction and waveguide mode shape. In particular, the reduction of losses becomes a critical factor in resonator devices. Titanium indiffused waveguides have the lowest losses seen from any nonlinear waveguide technology, with reliably measured (using cavity resonances \([20]\)) losses as low as 0.02 dB/cm \([11]\). Ridge waveguides are not far behind, with measured losses as low as 0.1 dB/cm, \([21]\). The increased losses of ridge waveguides is, however, compensated in part by a larger nonlinearity. Ridge waveguides have demonstrated second harmonic conversion efficiencies of around 240\%W\(^{−1}\)cm\(^{−2}\) (for SH at 340nm) \([7]\) whilst the titanium indiffused waveguides produced in our group have shown second harmonic conversion efficiencies of up to 14\%W\(^{−1}\)cm\(^{−2}\) (SH at 775nm). The maximum output power of a device will be decided by thermal and photorefraction effects within the waveguide. For indiffused waveguides it is possible to reduce photorefraction via sample heating, whereas doping techniques can be utilised in ridge waveguides \([22]\).

Due to the lower losses expected from titanium indiffused waveguides, the resonator was produced using this technology. Indiffused waveguides also have a very high spatial overlap with single mode fibres (of up to around 94\%). The disadvantage of titanium indiffused waveguides is the presence of photorefraction. Photorefraction is the migration of free carriers due to impurities in the wafer, typically Fe, that act to vary the electric field across the sample \([23]\). Due to this fact, it is virtually impossible to estimate the effect of photorefraction on device stability. Even with relatively small input powers this effect can cause a change in the refractive index of the material over time scales of tens of minutes as the dynamics stabilise \([23]\). Whilst this effect can be compensated for, at higher powers it is expected that catastrophic photorefraction will occur and will produce large amounts of noise on the produced SHG \([24]\).

Waveguides are fabricated in z-cut LiNbO\(_3\) by an indiffusion of lithographically patterned 7 \(\mu\)m wide, 80 nm thick titanium strips. The diffusion is performed at 1060 \(^\circ\)C for 9 hours in oxygen atmosphere. In a subsequent second lithography step, an insulating photoresist pattern is defined which is used for field assisted periodic domain inversion. We have chosen a poling period of approximately 16.9 \(\mu\)m to achieve the desired Type 0 quasi-phase matching, where all interacting fields are in the TM polarization. A short sample length of 8 mm long is chosen as a smaller sample is easier to stabilise in temperature.
and ensures that phase matching is uniform across the entire sample.

In order to optimise the conversion efficiency, one needs to correctly choose the mirror coating reflectivities. We choose to have the second harmonic exit the rear of the sample whilst the pump enters through the front. The rear surface therefore has an anti-reflection (AR) coating at 775 nm and a high-reflectivity (HR) coating at 1550 nm. The front surface is coated with a 77% mirror at 1550 nm and a HR coating at 775 nm. The 77% coating is chosen to achieve critical coupling of the pump assuming intra-cavity losses of 0.07dB/cm [12]. The coatings for the device are produced in-house using ion-beam assisted vapour deposition. Glass “blanks” are coated in the same coating run and from these one can accurately determine the properties of the coatings. The HR coatings are expected to have a reflectivity greater than 99%, and AR coatings a reflectivity of around 0.5%.

3 Waveguide Resonator Characterisation

3.1 Linear Properties

We begin by measuring the linear properties of the device at the fundamental wavelength of 1550 nm. The experimental layout is shown in Figure 1. The waveguide is pumped by a Tunics tunable C-band laser that is amplified using an EDFA. The power is fine-tuned using a half-wave plate followed by a polarising beam splitter. A dichroic mirror before the input to the waveguide can be used to measure the amount of second harmonic light leaking from the coating on the front surface. A second dichroic mirror at the exit of the waveguide separates the transmitted pump light from the generated SH light. The amount of power in this field is then attenuated and measured using a photodetector.

For accurate conversion efficiency measurements the coupling between the (fibre-coupled) laser mode and the waveguide mode is first precisely determined. The coupling of the laser beam into the mode of the waveguide is optimised and the light transmitted through the cavity is then coupled into a fibre as shown in Figure 1. The laser light is then disconnected and reconnected to this rear fibre-coupling and the light is shone through the waveguide in the reverse direction. By removing the Faraday isolator one can measure the amount of power before and after the first fibre-coupling to achieve an accurate measure for the overlap. From this measurement, the overlap between the fibre mode and the waveguide mode is determined to be 0.93±0.02.

The fundamental wavelength resonator properties are determined at a wavelength 10 nm away from the phase-matching temperature, well outside the phase matching bandwidth but near enough to the operational wavelength such that the properties of the coatings do not significantly vary. The wavelength is then scanned over a cavity resonance, allowing one to measure the transmitted power on-resonance and
the amount of power on and off-resonance in reflection. From these parameters the loss of the waveguide and the reflectivity of the cavity HR mirror can be precisely determined if the reflectivity of the front mirror and the incident power is precisely known.

Approximately 300µW of power is coupled into the waveguide cavity. On reflection we find that the power on resonance is 36±1% of the power off resonance and the transmitted power on resonance is found to be 6.3±0.1% of the power entering the cavity. Calculating the best fit using the standard treatment (see for example [25]) one finds that the intra-cavity loss at the fundamental wavelength is 0.16±0.01dB/cm and the reflectivity of the rear mirror at the fundamental wavelength is 99.4±0.1%. These values result in an expected (off phase matching) cavity finesse of 20, a free spectral range of 8.7 GHz and a cavity linewidth of 440 MHz. The loss is unfortunately higher than desired, but it is necessary to find a waveguide with the right phase matching conditions, high nonlinear efficiency and low losses.

This waveguide was the best compromise of the three parameters on this particular device.

3.2 Conversion Efficiency

With the fundamental cavity well characterised, we now turn our attention to the nonlinear properties of the device. The fundamental power entering the waveguide is varied through rotation of a half-waveplate in the beam path and the fibre amplifier gain. The wavelength of the laser is then scanned such that the optimal cavity resonance, the one that is closest to the centre of the phase-matching curve, is found. The wavelength of the laser is then adjusted at each power setting to ensure that thermal effects do not shift the cavity from the phase-matching condition. The generated second harmonic power on resonance is detected on a photodiode after attenuation via a calibrated neutral density filter.

Figure 2 shows the results of the second harmonic power run. The dotted line shows the expected performance of the device, where the only free parameter is the nonlinear coupling strength. In order to uncouple possible high power effects, such as photorefraction, the nonlinear coupling strength was found from a fit with low input power, as shown in the inset. At these low powers the nonlinear coupling
strength is found to be \( g = 853 \times 10^3 \text{ s}^{-1/2} \), matching very well with the data.

This value for the nonlinear efficiency was then used, along with the previously determined losses of the system to create the model indicated by the dotted line. Of note is that the output of the waveguide resonator is in strong accord with the predicted theory. This indicates that power related effects that may reduce the conversion efficiency, such as photorefraction, are not significant at these power levels and at this operating temperature.

Whilst photorefraction does not seem to reduce the produced SH power in the power range shown in figure 2, the output power was seen to fluctuate at fundamental input powers of 140 mW and above. This is perhaps an indicator of the onset of catastrophic photorefraction for this particular waveguide. However, due to the nature of the impurities, this limit will change from waveguide to waveguide and sample to sample. Nevertheless, we have shown that it is possible to produce large levels of second harmonic power from titanium indiffused waveguides.

4 High Power Limitations

The high power performance of the device is limited by photothermal and photorefractive effects. These effects are difficult to distinguish between because they are both expected to shift the cavity resonance in a similar fashion. It is expected that as the device produces more power the magnitude of these effects will increase and the task of keeping the resonator on resonance will become more difficult.

Whilst it is difficult to get a quantitative analysis of these effects, it is possible to look at them qualitatively. By scanning the frequency of the laser one can scan over the cavity resonance approaching from both high and low frequency sides whilst detecting the transmitted power. The presence of photothermal heating and/or photorefraction will produce a cavity scan that is asymmetric.

Such a cavity scan is shown in Figure 3, where approximately 110 mW of fundamental light is incident on the cavity. The direction of the laser frequency scan (scanned using a sawtooth function) is reversed at around zero seconds. The black trace shows the transmitted fundamental power when the cavity temperature is held at phase matching, resulting in a second harmonic power of around 70 mW. We note that the Airy function at this power level is not symmetric, indicating some minor amount of photothermal and/or photorefractive effects.

To investigate the wavelength dependence of the asymmetry the frequency of the laser was varied, such that the device was far from phase matching and no second harmonic power was produced. The transmitted power was again measured as the cavity was scanned and is shown by the blue trace. We immediately see that the cavity bandwidth has reduced due to the absence of nonlinear interaction, as expected. Perhaps surprisingly, however, a large asymmetry is still seen. Photorefraction is typically expected to have a very strong dependence on wavelength, whilst one might expect absorption to have a slight dependence on wavelength over this range. Therefore the observed results are consistent with a similar absorption at both wavelengths and only a minor contribution from photorefraction effects on the timescales of the scan. This is perhaps a surprising result and will be investigated further.

5 Stability

The stability of frequency conversion devices is a critical factor in many applications. One requires device stability that is at least equal to the required measurement time. Therefore, a preliminary investigation into device stability over longer time periods is undertaken. Due to the narrow linewidth of the cavity
Figure 3: Cavity scan with approximately 110 mW of fundamental power entering the sample. The blue trace is with the temperature far from phase matching while the black trace is on phase matching. The frequency of the laser is scanned with a sawtooth function and the sawtooth reverses direction at zero seconds. The oscillation in power is due to interferences caused by the frequency scan.

resonance this requires very stable, fine temperature tuning and for greater stability, some form of feedback that locks to the cavity resonance.

The issue of stability is addressed in two steps. The first step is to optimise the standard temperature loop. The 2-stage oven is enclosed in a Teflon housing and is then encased in a larger housing with openings only for the input and output fields. With this setup the temperature of the cavity is stable to a couple of millikelvin or better and this is enough to ensure that the cavity resonance is held, at low input powers and without the PDH loop, on the minute time scale. This scheme is limited because it does not sense the resonance condition. As such, system drifts may force the cavity off resonance in a way that is not sensed by the temperature sensor in this loop and are therefore not compensated. A second step is required to provide stability over longer time scales and at higher powers.

The second step is the PDH locking loop which directly senses the resonance condition, thereby providing a means of compensating system drift over longer times. The field entering the waveguide resonator is phase modulated via an electro-optic modulator at 25 MHz, as shown in Figure 1. These sidebands are well within the cavity linewidth and as such are transmitted through the cavity with the carrier and are detected at a photodiode. This signal is then fed into a Toptica Digilock system, therein undergoing mixing and filtering to produce the error signal. This error signal is then used to lock the system to resonance via feedback. It is possible to achieve this feedback via two methods; the first is by feeding back to the temperature controller to provide an offset, and the second by feeding back to the laser frequency. Feeding back to the laser provides a much faster lock but results in the centre frequency of the laser shifting, which may be an unwanted effect for some applications.

The performance of both locking schemes is illustrated in Figure 4. The temperature feedback lock is performed with approximately 30 mW of fundamental field entering the cavity, resulting in approximately 10 mW of second harmonic power whilst the laser feedback scheme has approximately 22 mW of fundamental field entering the cavity and 9 mW second harmonic power exiting the system. As expected, the temperature feedback scheme does not perform as well as the laser frequency feedback, an accumulated
offset over time is observed, likely due to the cavity resonance condition moving away from the peak of the phase matching. The laser feedback scheme has been locked stably for more than 6 hours, the drift of which is not greater than shown in Figure 4 and can be locked stably with output powers up to and including 50 mW. Beyond this output power the device becomes unstable, the reason for which is currently under investigation. The performance of both schemes far exceeds the requirements for many experiments. Heating of the sample at higher input powers makes locking more difficult, but is currently under investigation.

6 Conclusion

In conclusion, we demonstrated a very high external conversion efficiency, high power second harmonic waveguide resonator device. This was achieved in an 8 mm long titanium indiffused lithium niobate waveguide device. With a 1550 nm pump field, an external conversion efficiency of 75% was measured output powers up to 110 mW were directly measured. Photorefraction was likely seen at output powers beyond this. The device was locked stably over an hour using a PDH scheme producing 10 mW of second harmonic via both a laser frequency and a temperature offset feedback scheme.

Funding

The authors acknowledge funding from the Gottfried Wilhelm Leibniz-Preis.

References


