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ELECTRIC-FIELD THERMALLY POLED OPTICAL FIBRES FOR QUASI-PHASE-MATCHED SECOND HARMONIC GENERATION

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Abstract

We report on quasi-phase-matched frequency doubling to the blue in electric-field poled optical fibres. An increase of a factor of ~10 in the conversion efficiency in comparison with the previous results is obtained. Our experiments show that the structure of the induced nonlinear grating is not uniform, both longitudinally and transversely. For this reason the value of the effective nonlinear coefficient is still far from the optimum expected from the measured value, through Maker's oscillation, for a uniformly poled fibre.

In centro-symmetric materials, such as glasses, second-order nonlinearities are normally forbidden. In recent years it has been discovered that a several electric field poling techniques result in the appearance of nonlinearities of order 1 pm/V [1,2,3], with some indications that even higher values (~10 pm/V) may be possible [4]. These nonlinearities can be exploited for electro-optics and nonlinear optical frequency conversion and put glass in the unexpected position of a potential competitor to crystals, such as lithium niobate (LN) and potassium tytanil phosphate (KTP).

Because of their high nonlinear coefficient (more than one order of magnitude than for glass), LN [5] and KTP [6] potentially offer higher efficiencies for quasi-phase-matched optical frequency conversion in a waveguide geometry. However glass has a lower dispersion than LN and KTP, thus greater bandwidths availability (more than one order of magnitude for the same device length) in nonlinear optical devices. This means that in glass the lower value of the nonlinearity could be compensated by increasing the length of the device, thus achieving the same efficiency as for LN and KTP without altering the frequency stability. For example one can calculate that a perfectly periodically poled fibre with an effective nonlinear coefficient of 0.32 pm/V (starting nonlinear coefficient in the uniformly poled fibre of 1 pm/V), core diameter of 3 μm, numerical aperture of 0.35, length of 5 cm, can produce ~5 mW of blue light at 440 nm, when pumped with 100 mW [7]. The acceptance bandwidth of such a device would be ~0.15 nm. These peformances are comparable with those achieved in periodically poled LN and KTP waveguides [5,6]. The low dispersion also gives glass potential advantages in the case of pulsed second-order nonlinear optical processes since the group velocity mismatch (GVM) between the pulses at different frequencies (which limits the effective interaction length) is in glass more than one order of magnitude less than in LN and KTP.

Compared to crystalline materials poled glass also offers lower fabrication costs and superior optical properties, such as lower loss and higher optical damage thresholds. In addition its use in a fibre configuration would simplify the optoelectronic systems and reduce the insertion loss and the packaging costs associated with coupling of discrete optical components.

Recently, periodically patterned second order nonlinearities have been created in optical fibres by thermal poling in vacuo and cw quasi-phase-matched second harmonic (SH) generation to the blue has been demonstrated [8]. The maximum SH power detected was ~400 pW, corresponding to a fundamental power in the fibre of ~100 mW. In that work, the blue light at 430 nm was generated in the higher order mode LP_{11}. Here we present blue light generation at 440 nm, in the fundamental mode LP_{01}, with an increase of a factor ~10 in the conversion efficiency in comparison with the previous results. The interaction with the higher order SH mode LP_{11} was suppresed by side-etching of the fibre surface.

The fibre used in the experiments was a D-shape fibre which had a Ge-doped silica core and a fused-silica cladding. The numerical aperture was 0.09, and the core and the outer diameters were 5.8 and 130 μm respectively. The distance between the core region and the plane surface was 5 μm. The poling technique, based on continuous electric field applied via aluminium electrodes at ~280 °C for ~10 minutes in vacuo, is the same as described in ref. 8. For the experiments we prepared three samples . The first sample (A) was initially etched in a HF/H_2O solution in order to reduce the core-surface distance from 5 to 1 μm and then uniformly poled over 10 mm. The second sample (B) was periodically poled over 6 mm with a pitch (including poled and non-poled sections) of 28 μm. The third sample (C) was initially etched as sample A and then was periodically poled as sample B.

Before working on quasi-phase-matched second harmonic generation (QPM-SHG) with samples B and C we started evaluating the nonlinear coefficient in sample A via measurements of Maker's SH oscillations using a cw Ti:sapphire laser, tunable from 780 to 900 nm, as the fundamental source. Fig.1 shows the SH power against fundamental wavelength for sample A and for an interaction between fundamental modes at both fundamental and SH wavelengths ($LP_{01}^{\omega} \longrightarrow LP_{01}^{2\omega}$). In a waveguide geometry [7], the SH power $P_{2\omega}$ is given by:

$$P_{2\omega} = \frac{8\,\omega^2\, d^{\,2}}{n_{2\omega}\, n_{\omega}^{\,2}\, \varepsilon_o\, c_o^{\,3}}\; \frac{P_{\omega}^{\,2}}{A_{OVL}}\; \frac{1}{\Delta\beta^2}\, \sin^2\!\left(\frac{\Delta\beta\, L}{2}\right) \rho$$

where ω is the fundamental frequency, P_{ω} is the fundamental power, d is the nonlinear coefficient, L is the device length, $n_{2\omega}$ and n_{ω} are the effective refractive indices at frequency 2ω and ω respectively, ε_o the dielectric constant in vacuum, c_o the speed of light in vacuum, $A_{OVL}=1/I_{OVL}^{\,2}$ is an equivalent area which depends on the overlap integral I_{OVL} between the interacting fields and the poled region, $\Delta\beta = \Delta\beta(\omega) = 2(\omega/c_o)(n_{2\omega}-n_{\omega})$ is the wave-vector mismatch and ρ is an enhancement factor which takes account of the multimode nature of our fundamental source [9]. For $\Delta\beta L \gg 1$, this expression describes the Maker's oscillation, i.e. in our case the nearly sinusoidal dependence of the SH power on the fundamental wavelength. One can easily confirm that the measured period of the Maker's SH modulation in fig.1 corresponds to a length of ~10 mm, indicating good agreement between theory and experimental results. The measured SH power was ~100 pW, corresponding to a fundamental power of ~ 70 mW. From these powers, assuming $\rho=2$, we evaluated d~0.7 pm/V. This value of d (~ $\chi^{(2)}/2$) corresponds to a second-order nonlinear susceptibility $\chi^{(2)}$ of ~1.4 pm/V, in good agreement with previous measurements [1-3].

After these preliminary SH measurements to determine the nonlinear coefficient we optically assessed samples B and C via QPM-SHG to the blue. Figs.2 and 3 show the SH power against fundamental wavelength for samples B and C, indicating for both samples the presence of interaction with both the fundamental SH mode $LP_{01}^{2\omega}$ and the higher order SH mode $LP_{11}^{2\omega}$ at a fundamental wavelength of ~880 nm and ~860 nm respectively. These wavelengths for QPM-SHG are in good agreement with the theoretical predictions which take account of both material and modal dispersion (effective refractive indices).

The fact that the interaction ($LP_{01}^{\omega} \rightarrow LP_{11}^{2\omega}$) between the fundamental mode LP_{01}^{ω} and the odd higher order SH mode $LP_{11}^{2\omega}$ is allowed indicates that the poled region is not centred with respect to the core. If it were centred the overlap integral between the interacting fields and the poled region would be zero because of the modes parity. In sample B the interaction with the higher order SH mode $LP_{11}^{2\omega}$ is stronger than in fibre C. This is probably associated with the increase of the core-surface distance from 1 to 5 μm. This increase is believed to rise the loss for higher order modes and to move the poled region more toward the centre of the core. In fact the poled region, located a few microns under the surface, and the core have approximatevely the same size and it is not surprising that they are more off-centre with respect to each other in sample B than in sample C.

The presence of strong side-peaks in figs. 1 and 3 is probably an indication of the fact that the grating is not uniform along the direction of propagation. This was confirmed by launching the beam from a 1.064 μm Q-switched and mode locked Nd:YAG laser transversely to the fibre. The beam was focussed in the grating region of the fibre and the corresponding SH near field was imaged by a CCD camera connected to a TV monitor. Fig. 4 shows clearly the presence of regions where the grating is almost absent (fig.4.a) together with regions where an evident periodic modulation of the nonlinearity is present (fig.4.b). We believe that the absence of the grating is mainly due to spreading of the poled regions. This is consistent with the fact that the regions, where there is no evidence of grating structure, provided a uniform SH signal rather than absence of SH signal (fig.4.a). Note that figs. 4.a and fig.4.b are on different scales. The side peaks (see figs. 2 and 3) are stronger in the case of sample B than of sample C. A possible explanation is that the location of the poled region with respect to the core varies longitudinally along the fibre, thus making the overlap integral longitudinally change. This is more likely to occur in fibre B than in fibre C and is equivalent to a grating longitudinally non uniform.

The maximum SH power detected for sample B was ~2nW, corresponding to a fundamental power in the fibre of ~230mW. For sample C these values were ~10nW and ~230mW respectively. From the above expression for the SH power one can estimate that the effective nonlinear coefficient d_{eff} (average over the whole 6 mm grating length) is >50 times smaller than the expected value of 0.22 pm/V (=d/π) for a perfect grating with an amplitude d of 0.7 pm/V (which is the nonlinear coefficient measured in the uniformly poled sample A). This degradation is probably due to the aforesaid non uniformity of the grating. In fact we observed during the experiment relative to fig.4 that the grating structure is limited to small regions, giving an equivalent total interaction length much less than the expected 6 mm.

In conclusion, QPM-SHG of 440 nm in a fundamental mode has been obtained in optical fibres with improved conversion efficiency and power levels compared to previous results [8]. The nonlinear coefficient of 0.7 pm/V, measured in a uniformly poled fibre, suffered of strong degradation when the fibre was periodically poled. We pointed out that the main reason of this degradation is the non uniformity of the grating structure due to spreading of the poled regions. We expect great improvements in efficiency and SH power by optimizing the uniformity of the grating and increasing the length of the grating.

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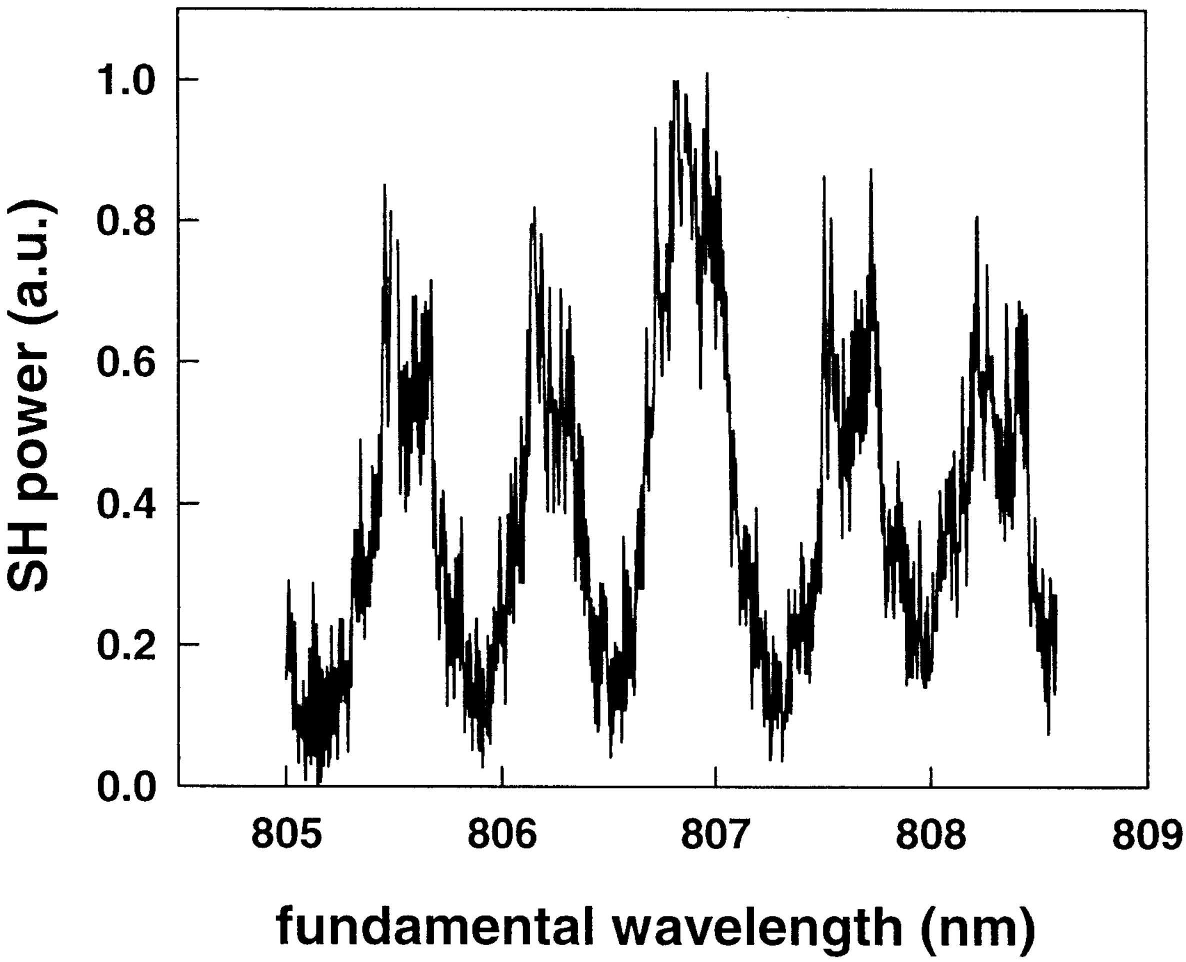
Figure captions

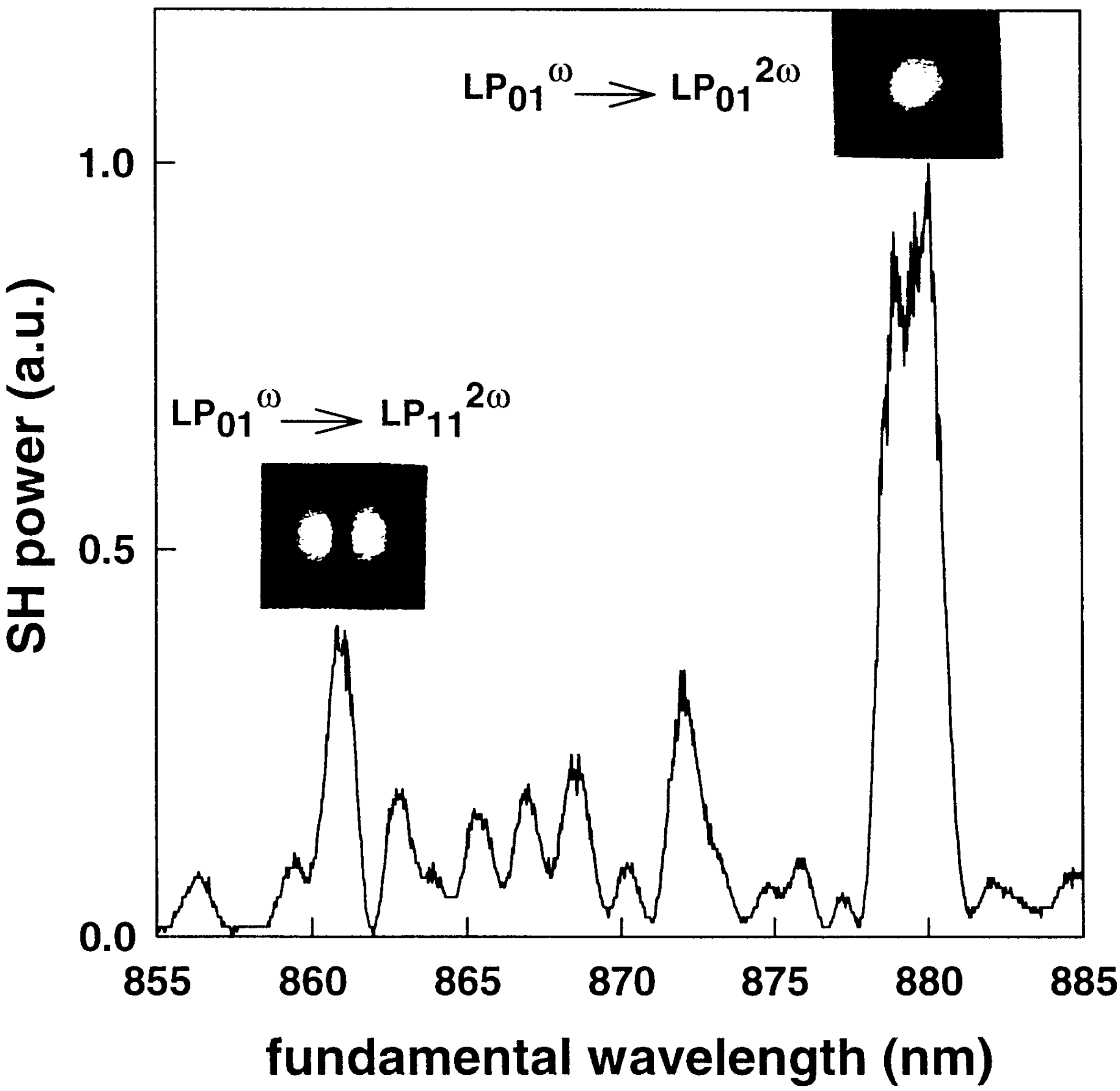
Figure 1 Second harmonic power against fundamental wavelength for sample A, etched and uniformly poled.

Figure 2 Second harmonic power against fundamental wavelength for sample B, periodically poled.

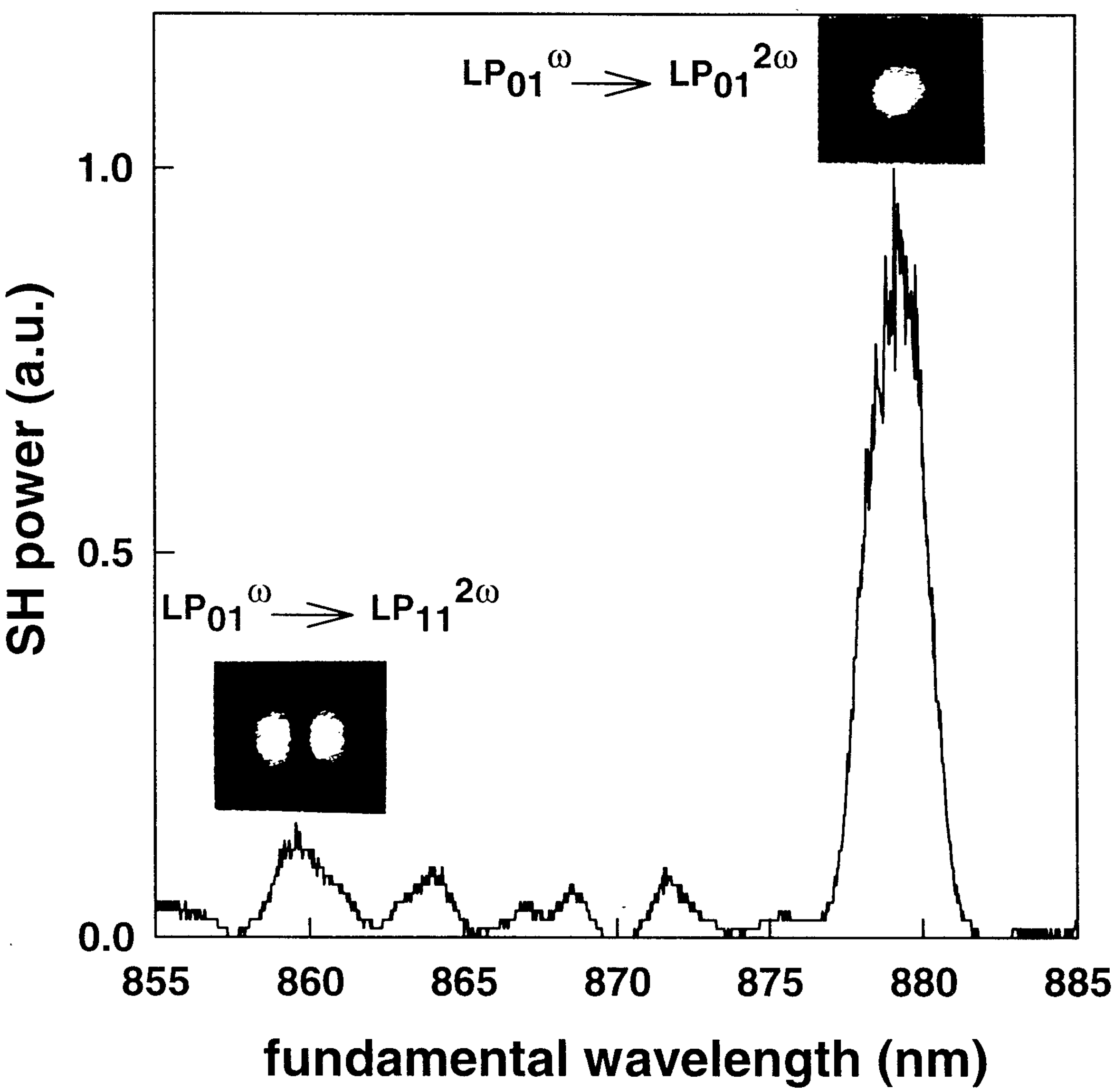
Figure 3 Second harmonic power against fundamental wavelength for sample C, etched and periodically poled.

Figure 4 Near field second-harmonic patterns, imaged by launching the fundamental 1.064 μm beam transversely to the fibre. There is evidence of regions where the modulation of the nonlinearity is extremely weak due to spreading of the poled sections (a) and particularly evident (b). Note that figures (a) and (b) are on different scales.

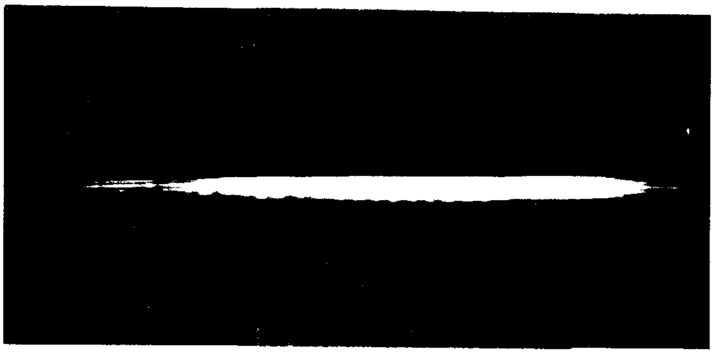

SH power (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
805
806
807
808
809
fundamental wavelength (nm)



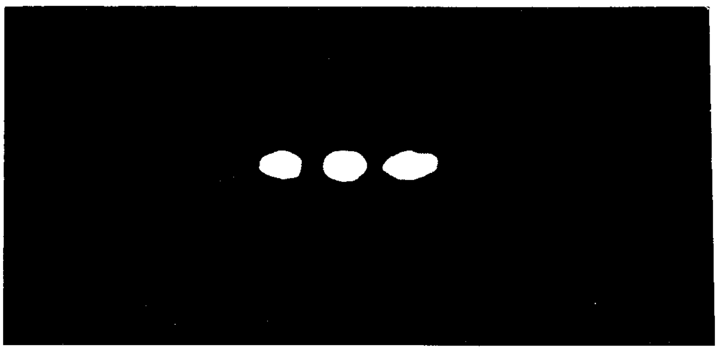
$LP_{01}^{\omega} \rightarrow LP_{01}^{2\omega}$
$LP_{01}^{\omega} \rightarrow LP_{11}^{2\omega}$
1.0
0.5
0.0
SH power (a.u.)
855
860
865
870
875
880
885
fundamental wavelength (nm)



$LP_{01}^{\omega} \rightarrow LP_{01}^{2\omega}$
$LP_{01}^{\omega} \rightarrow LP_{11}^{2\omega}$
SH power (a.u.)
1.0
0.5
0.0
855
860
865
870
875
880
885
fundamental wavelength (nm)



(a) 28 μm



(b) 28 μm