Spectral characterisation of $\chi^{(2)}$ grating

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Abstract : We describe a simple technique to characterise nonlinear gratings for quasi-phase-matched structures. The method is based on the analysis of the spectral characteristics of the second-harmonic beam generated in a pulsed regime. The potential of such technique is experimentally demonstrated in periodically poled D-shaped silica fibres, a promising second order nonlinear material.

Introduction**:** A widely used technique for the characterisation of second-order nonlinear gratings consists in measuring the quasi-phase-matching (QPM) curve for second-harmonic generation (SHG). This is achieved by continuously varying a control phase-matching parameter, usually the sample temperature or the fundamental wavelength. In the case of a perfect periodic structure, the experimental curve should have the familiar $sinc^2$ shape and in general its features reveal important information on the length, the chromatic dispersion and the regularity of the nonlinear grating. In particular, the Full Width at Half Maximum (FWHM) is related to the length of the grating, to the spatial distribution of the period and to the chromatic dispersion. Also, the relative height of possible secondary lobes compared to the main one is an indication of the grating homogeneity, which can be affected by different kind of imperfections (e.g. random errors in the duty-cycle, in the period, in the nonlinear modulation, etc.). However techniques which involve temperature or wavelength tuning for the measurement of the phase matching curves, exhibit some drawbacks, especially for long gratings. Indeed, if temperature tuning is used, it proves difficult and time consuming to achieve a uniform temperature over the whole length of the sample. Any temperature gradient will lead to an uncontrollable chirp in the period, resulting in a phase matching curve very different from the expected one. If the fundamental wavelength is tuned, a very fine scan step might be required, especially in the case of long gratings, which present very narrow phase matching curves. To overcome these drawbacks we propose a different method that does not need tuning of any parameter and involves short laser pulses and relatively long nonlinear gratings.

Description**:** The proposed technique will be applied to the case of SHG of ultra-short pulses in QPM structures without depletion of the pump and it is essentially based on the analysis of the spectrum of the generated second harmonic. SH can be treated as resulting from the filter response of a nonlinear medium to an input fundamental (F) pump pulse. This approach was introduced for example in [1,2,3] for analysing the influence of the Group Velocity Dispersion (GVD) on SHG of ultra-short pulses, and recently extended to QPM structures in [4]. In the frequency domain the SH field $A_2(z, \omega)$ is given by [3]:

$$A_2(z,\omega) = h(z,\omega,\eta).f(\omega) \quad (1)$$

where $h(z,\omega,\eta)$ is the Fourier transform of the response of the nonlinear grating, $\eta = 1/v_g^{SH} - 1/v_g^F$ is the group velocity mismatch (GVM) between SH (v_g^{SH}) and F(v_g^F) and $f(\omega)$ is the Fourier transform of the square of the fundamental field. Two different cases can be distinguished, according to the ratio of grating length L to the walk-off length $L_{wo}=\tau_p/\eta$, where τ_p is the pump pulse duration:

Case 1. If $L \ll L_{wo}$, $h(L,\omega,\eta)$ is much broader than $f(\omega)$ resulting in a spectrum of the SH completely defined by $f(\omega)$. The SH spectrum doesn't give in this case any useful information on the grating characteristics.

Case 2. On the contrary, if $L \gg L_{wo}$ $f(\omega)$ is much broader than $h(L,\omega,\eta)$, therefore the spectrum of the SH pulse is in directly related to the Fourier transform of the impulse response of the grating. This is at the base of the characterisation technique we proposed.
As an example, for a perfect grating of length L in a first order QPM configuration, $h(z,\omega,\eta)$ is given by [3] :

$$h(z,\omega,\eta) = -\rho_2 . L. \mathrm{sinc}(L\eta\omega / 2)$$

where ρ_2 is the non linear coupling coefficient proportional to the second order nonlinear susceptibility [3]. If $L \gg L_{wo}$, we can infer the length of the grating from the FWHM of the SH spectrum, knowing the dispersion properties of the material. Note that the condition $L \gg L_{wo}$ is easily achieved for short pulses: for example in the case of periodically poled $LiNbO_3$ and 100fs fundamental pulses $L_{wo} < 1$mm at 1.5µm, whereas for the same pulse in a periodically poled silica fibre $L_{wo} < 1$cm.

Experimental and simulation results: Although our method is more general, we tested it on D-shaped QPM fibres obtained by thermal poling [5]. The 7.5cm long grating presented a period for SHG peaking at a fundamental wavelength around 1530µm. Fig 1a) illustrates the first case, where $L \ll L_{wo}$. The experimental phase matching curve (circle) obtained with 2 ns long pulses, together with the theoretical curve (full line) are shown. The experimental curve is clearly narrower than the expected one, and hints to a grating longer than the fabrication process itself would allow, which is obviously not possible. The other possible explanation of this narrowing is the presence of irregularities along the grating [6], but for our fibres this seems to be rather unlikely if we take into account the relatively high observed SHG efficiency [5]. In addition useful information on the grating is lost due to washing out of details by low wavelength resolution. Fig. 1b) instead, referring to the second case, shows the experimental SH spectrum (circle), obtained with 100fs pulses, together with the expected spectrum (full line). Clearly, the fit shows that the grating is homogeneous along the whole 7.5cm length and demonstrates the usefulness of the method as well as its simplicity.
In order to give further proof of the potential of the technique, we present a second example of case 2, using 2cm long nonlinear grating and 100 fs fundamental pulses. Fig. 2a) shows the measured SH spectrum. Fig. 2b) and 2c) are the corresponding calculated spectra for a grating with no imperfection and with one irregularity, respectively. A good fit to the experimental data is obtained if one assumes a 0.71cm long imperfection located 1.023cm away from the

fibre input end. The sensitivity of the characterisation procedure is illustrated in figure 2c), where the shape of the SH spectrum for irregularities located at the same position and possessing different lengths (0.45cm and 0.85cm). However other more complex configurations, involving multiple defects could in principle lead to a good fit to the data.

Conclusion: We propose a very simple alternative to the measurement of phase-matching curves for the characterisation of $\chi^{(2)}$ gratings. It is based on the measurement of the SH spectrum for fundamental pulses short enough so that the length of the grating is much longer than interaction length. The technique is general and particularly well suited for investigation of long nonlinear gratings, which are of particular interest for efficient second order parametric interactions in poled optical fibres.

References**:**

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Figure captions

Figure 1: Experimental (circle and dotted line) and theoretical (full line) phase matching curves for a 7.5cm long grating. The pump pulse duration is a) 2ns and b) 100fs.

Figure 2: SH spectrum for a 2cm long grating. The fundamental pulse duration is 100fs. Figure 2a): measurement. Figure 2b): theory for a perfect grating. Figure 2c): theory for a grating with a 0.71cm long defect situated at 1.023cm from the input (thick line), with a 0.85cm long defect in the same position (thin line), with a 0.45cm long defect in the same position (dotted line).

Figure 1

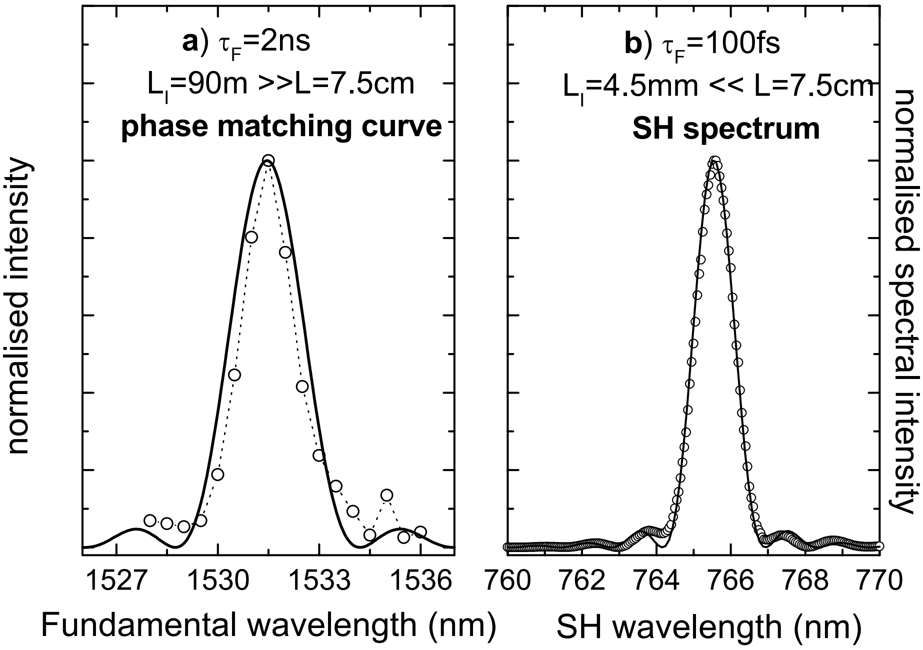
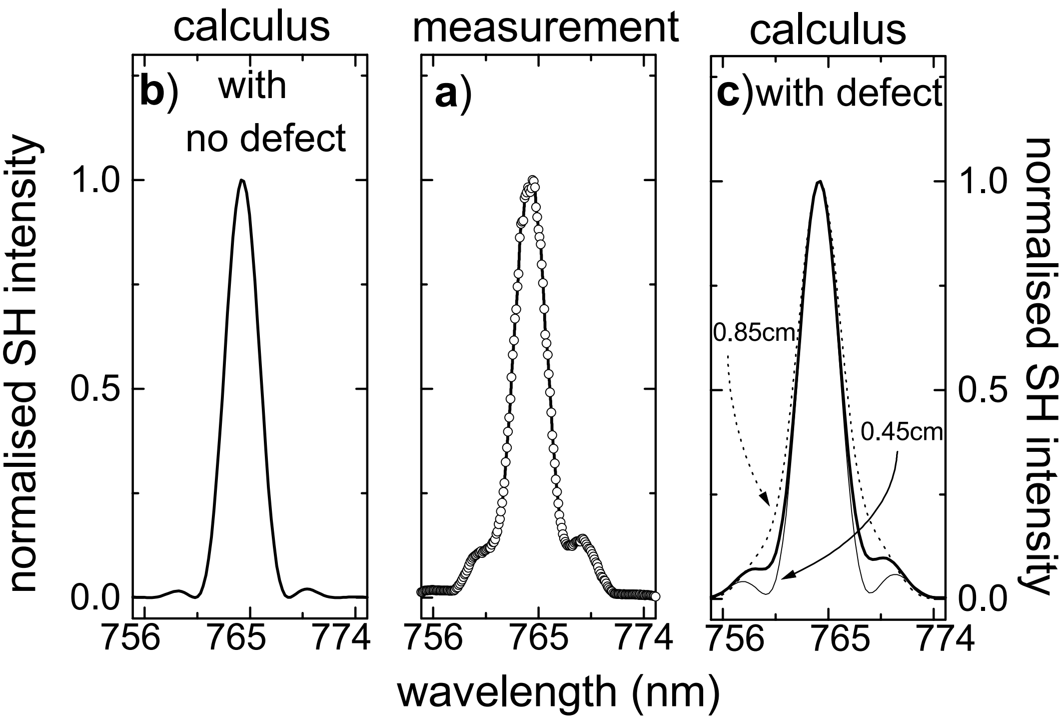

a) τ_F=2ns
L_l=90m >>L=7.5cm
phase matching curve
normalised intensity
1527
1530
1533
1536
Fundamental wavelength (nm)
b) τ_F=100fs
L_l=4.5mm << L=7.5cm
SH spectrum
normalised spectral intensity
760
762
764
766
768
770
SH wavelength (nm)

Figure 2


calculus
measurement
calculus
b)
with
no defect
a)
c)with defect
normalised SH intensity
normalised SH intensity
1.0
0.5
0.0
0.85cm
0.45cm
756
765
774
wavelength (nm)