Practical technique for measurement of second-order nonlinearity in poled glass

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A simple and nondestructive technique for measuring the thickness of the nonlinear optical layer in thermally poled glass, providing a minimum measurable thickness of 4 and 1 μm resolution, is demonstrated. This technique is generally applicable to other nonlinear optical layers as well.

Introduction: Thermal poling enables permanent second-order nonlinearities (SON) in glasses to be produced [1]. These nonlinearities can be exploited for all-fibre electro-optic switches and wavelength converters, with the potential for integration in telecommunication systems [2]. Efforts are focused on the search for novel glass systems and optimum poling conditions to obtain the highest SON [3], although a reliable determination of the value of $\chi^{(2)}$ is still an issue.

The Maker's fringe technique (MFT) is commonly used to evaluate the $\chi^{(2)}$ of nonlinear materials. In the MFT a laser beam is focused onto the sample of nonlinear length L_0 at different angles and used as a pump to generate second-harmonic (SH) light [4]. The measured SH intensity is proportional to the product $(\chi^{(2)} L_0)^2$. Hence, the ability to determine the value of $\chi^{(2)}$ requires the knowledge of L_0 that is possible, in the MFT, only if the fundamental beam travels through the nonlinear medium for a length L at least equal to one coherence length ($l_c \sim 24$ μm in silica). In principle it is possible to make L longer than l_c by probing at large angles, but the total internal reflection (TIR) limits the minimum measurable thickness to $L_0 = l_c \cdot \cos(\theta_{TIR})$, i.e. about 18 μm for silica. In poled glasses the thickness of the nonlinear layer is usually smaller than this value ($\sim$10 μm) and therefore the MFT cannot be used. In the literature reported values of $\chi^{(2)}$ are sometimes only estimated, which gives less significance to the achievements in this area. Hence, the importance of a reliable and practical technique to measure the thickness of the induced nonlinear layer.

Modified MFT setups, with the sample sandwiched between a couple of either prisms or glass hemispheres, were proposed to avoid the limitation imposed by the TIR, so that the condition $L > l_c$ is achieved [5, 6]. A variant of the MFT [7], two fundamental beams are employed, at an angle, to produce a noncollinear SH beam which has much smaller coherence length ($\sim$2 μm in silica), compared to the collinear ones, so that $L > l_c$ is easily achieved. Chemical etching in which the etched depth is monitored interferometrically, was also used as an independent measurement of L_0 [8].

In this Letter we propose a nondestructive and more practical technique for measuring the nonlinear thickness of poled glasses. The technique is based on the interference between SH light beams which are generated by two identically poled glasses pressed together in a stack. Thicknesses, as small as 4 μm, can be measured with a resolution better than 1 μm. The technique has been tested on a set of thermally poled silica glasses.

Results and discussion: During thermal poling an electrostatic field ($\vec{E}_{dc}$) is frozen in a thin layer close to the surface of the glass which was in contact with the positive electrode. $\vec{E}_{dc}$ couples with the intrinsic $\chi^{(3)}$ of the glass to give $\chi^{(2)} = 3\chi^{(3)}\vec{E}_{dc}$. In the technique presented hereafter, a stack is made by pressing in contact two identically poled glasses (alternatively the same one cut in two pieces) with the nonlinear layers facing each other. The stack is then probed just as in the MFT (Fig. 1, inset). In our 'stack' Maker's fringe technique (SMFT), each of the two nonlinear layers generates an SH light beam which interferes with the other one and the SH power at the output of the stack depends on the relative phase between the two SH beams. The key point of the SMFT is that, at a given angle, the *ratio* of the SH powers measured for the stack ($P^{2\omega}_{stack}$) and for the single glass ($P^{2\omega}$) is independent of the value of $\chi^{(2)}$ and only depends on L_0. It should be noticed that, at the interface between the two glasses, the sign of the nonlinearity is reversed because of the opposite orientations of $\vec{E}_{dc}$. It follows that the mathematical treatment typically used in quasi-phase-matching (QPM) analysis is applicable to the SMFT as well. Assuming a uniform $\chi^{(2)}$ across the nonlinear layer, it is possible to show that

$$\frac{P^{2\omega}_{stack}}{P^{2\omega}} = 4\sin\left(\frac{\pi}{2}\frac{L_0}{l_c}\frac{1}{\cos(\theta_{2\omega})}\right)^2 \qquad (1)$$

where $\theta_{2\omega}$ is the SH internal propagation angle. For $L = L_0/\cos(\theta_{2\omega}) < l_c$, the function described in (1) is monotonic so that, by inverting it, L_0 is uniquely determined in this range. Hence, we found the interesting result that the SMFT is complementary to the MFT and extends its range to smaller values of L_0. $L = l_c$ is the condition for QPM and, in fact, $P^{2\omega}_{stack}$ is maximum in this case. It should also be pointed out that, with the SMFT, the measurement of the thickness is further simplified, compared to other techniques, as the angular dependence of the Fresnel transmission losses and of the beam size correction factor do not have to be taken into account.

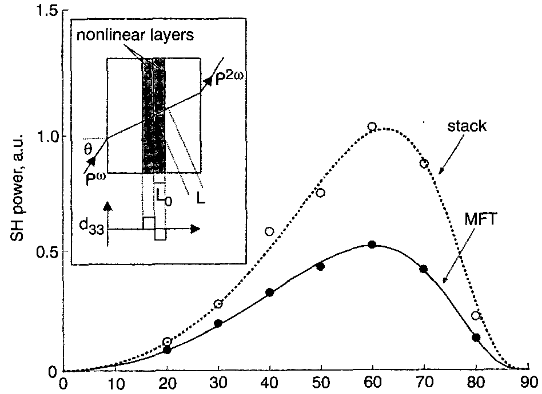

Fig. 1 *SH power against external angle θ, measured for single poled glass (solid symbols) and for stack of two identically poled glasses (open symbols)*

Data refers to sample poled for 90 min. From the ratio of SH powers at each angle, the thickness of the nonlinear layer is calculated and its value used to fit the data (solid and dashed lines)
Inset: Schematic diagram of stack made by pressing two poled glasses together

The major sources of experimental errors are found in the measurement of the ratio of the SH powers and in the reading of the incident angle. The former contribution to the error is more important when L_0 is small, whereas the latter dominates when L_0 is large, especially if the sample is probed at large angles.

MFT and SMFT measurements were performed (Fig. 1) on a set of 200 μm-thick silica plates (Herasil 1), poled in air for 7, 15, 30, 45 and 90 min at 280°C, with 4 kV applied voltage. The assessment of the method is performed using a modelocked and Q-switched Nd:YAG laser ($\lambda = 1064$ nm) with a focused spot radius of $w_o = 26$ μm. The corresponding Rayleigh range ($2z_0 \sim 4$ mm) is long enough to encompass the whole stack, so that the effect of spherical aberrations and astigmatism is reduced. No index matching fluid is used between the samples, since its larger dispersion (compared to air) would introduce a phase shift between the SH beams generated by the two layers, randomly modifying their interference condition and making it impossible to retrieve the value of L_0. According to (1) the nonlinear thickness is calculated, for each sample, at different angles (Fig. 2). As in the standard Maker's fringe technique, once determined, the value of L_0 is used to fit the MFT pattern (Fig. 1) and $\chi^{(2)}$ is evaluated by comparison with a crystal of known nonlinearity. Using an α-quartz crystal as a reference ($d_{11} = 0.3$ pm/V) a $\chi^{(2)}$ of 0.14 pm/V is determined in the sample poled for 90 min. Although this is a rather small value, it must be stressed that our aim in this Letter is the demonstration of the technique and not the achievement of high $\chi^{(2)}$. The evolution of L_0 with poling time agrees well with the result of previous studies [9] (Fig. 3). Each datum for L_0 shown in Fig. 3 is the average of the values obtained at different angles (Fig. 2). The experimental errors, evaluated from the standard error of the mean, are in general below 10%.

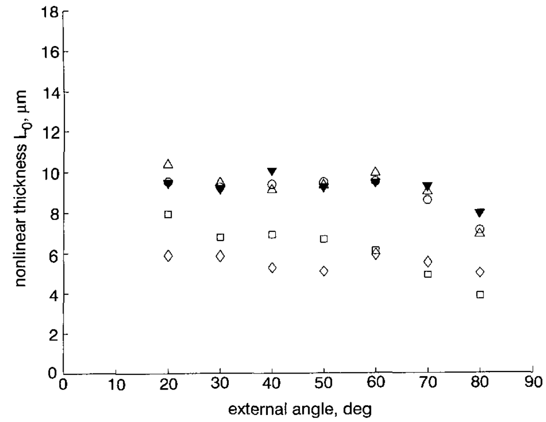

Fig. 2 *Thickness of nonlinear layer in set of silica plates poled for different times*
◇ 7 min
□ 15 min
△ 30 min
▼ 45 min
○ 90 min

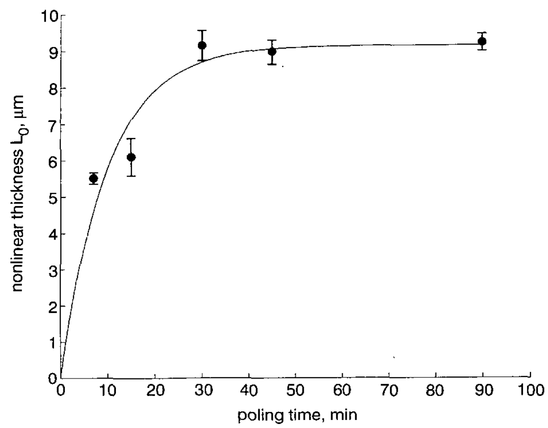

Fig. 3 *Measured values for nonlinear thickness against poling time*
——— best stretched-exponential fit for experimental data

Conclusion: We have demonstrated a practical, simple and non-destructive technique for measuring the nonlinear thickness in poled glasses which will provide reliable evaluation of the induced $\chi^{(2)}$. Moreover, the technique is not restricted to poled glasses but it is applicable to any nonlinear optical layer.

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Variable optical delay circuit using highly nonlinear fibre parametric wavelength converters

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A variable optical delay circuit that employs a fibre loop with highly nonlinear fibre parametric wavelength converters is described. The delay time is determined from the number of circulations, which is controlled by the initially selected wavelength of the signal. No additional amplifier to compensate for the circulation loss is required.

Introduction: Optical packet switching will become a key technology in the future. Optical packet switching networks need optical packet buffers to resolve packet contention. Recently we demonstrated a variable optical delay circuit that employed an optical loop and SOA-XPM-based wavelength converters [1]. The delay circuit was capable of regenerating signals, handling variable-length packets, and reducing the volume of buffers. However, it was necessary to install the same number of converters as the number of circulations.

In this Letter we present a novel variable optical delay circuit using highly nonlinear fibre (HNLF) parametric wavelength converter units [2, 3] and an optical loop. With this architecture, only two wavelength converters are required regardless of the number of circulations. The high wavelength conversion efficiency means that no optical amplifier is needed inside the optical loop to compensate for the circulation loss, and signal degradation by additional amplified spontaneous emission (ASE) noise can be prevented.

Operating principle: Fig. 1 shows the concept of the optical delay circuit described here. The delay circuit consists of a wavelength converter, an optical loop, an optical coupler with two arms connected to form the optical loop, a wavelength shifter, and an optical drop module. In the wavelength converter, the wavelength of each input packet is converted to an initial wavelength $\lambda_{initial}$ that controls the delay time. The wavelength-converted optical packet is fed into the optical loop via the coupler. The wavelength shifter located in the optical loop gives optical packets a uniform wavelength shift per circulation. Therefore, the initial wavelength of the optical signal shifts sequentially. When the wavelength reaches the output wavelength, λ_0, the optical signal exits from the optical drop module. Consequently, the circulating number, namely the delay time, is controlled directly by the initial wavelength.

A wavelength shift can be attained by cascading two multichannel wavelength converters. Although a wavelength shifter with quasi-phase matched $LiNbO_3$ devices has already been reported [4], the conversion efficiency is still not sufficient to compensate for the circulation loss. In this Letter, we focus on two HNLFs as the shifter, since they can exhibit a large wavelength conversion gain based on four-wave mixing [5]. The