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Parametric Fluorescence in Periodically Poled Silica Fibres

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Abstract

We report the first observation of Quasi-Phase Matched parametric fluorescence from a periodically-poled silica fibre. A pair-photon production rate of more than 100 MHz around 1532 nm, was achieved in second-order nonlinear gratings for 300 mW of pump power at 766 nm. These results are very promising for the realisation of reliable all-fibre single photon sources for quantum cryptography systems and metrology applications.

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The recent demonstration of highly efficient Second-Harmonic Generation (SHG) in periodically poled silica fibres [1], has opened new prospects for the realisation of second-order nonlinear optical processes in all-fibre devices. Thermal poling has been shown to induce a significant and permanent second-order susceptibility ($\chi^{(2)}$) in silica and germanosilicate optical fibres [2,3]. Here it is used to realise periodic second-order nonlinear patterns through the application of a high voltage at elevated temperature to a periodic anode [4]. The periodic non-linearity compensates for the momentum mismatch in the nonlinear interaction providing Quasi-Phase Matching (QPM) [5]. As we already mentioned [4], compared to crystal waveguides, periodically poled silica fibres (PPSF) despite having a lower effective nonlinear coefficient d_{eff}, offer a longer interaction length (L) for the same bandwidth and higher damage intensity threshold (I), thus achieving a similar value for the relevant figure of merit $d_{eff}^2\, L^2\, I$.

Given the achieved SHG efficiencies, the next step is the implementation of Parametric Fluorescence (PF), a special case of Difference Frequency Generation (DFG). PF is at the heart of optical parametric oscillators and represents a unique source of correlated photon pairs, whose peculiar characteristics make them extremely useful for the study of quantum interference, quantum cryptography [6] and for metrology applications. In particular so far, PF achieved in birefringence phase matched crystals, has been used to verify non-local interference to several kilometres in fibres [7], for novel secure communications and rangefinding and for the absolute measurement of the quantum efficiency of photon counting detectors [8].

QPM-PF was already observed in periodically poled $LiNbO_3$ optical waveguides [9]. After the observation, more than 10 years ago, of photoinduced $\chi^{(2)}$ effects in optical fibres [10–13], we report the first observation of parametric fluorescence from QPM periodically poled silica fibres.

The fabrication of the PPSF samples has already been described elsewhere [4]. The D-shape fibre used had numerical aperture (NA) ~ 0.19, core diameter of 6 μm, outer diameter of 300 μm and, after preliminary etching, a distance flat surface to core of 5 μm. The chosen period for the patterned aluminium anode, $\Lambda = 56.5\ \mu$m, resulted in QPM-SHG around 1532 nm, with a normalised conversion efficiency $\eta_{SH} \simeq 4 \cdot 10^{-3}$ %/W (see Ref.1).

Fig.1 shows the setup for the parametric fluorescence generation. The pump beam from a CW Ti:sapphire laser was coupled into the fibre sample trough a x40, NA=0.6 microscope objective.

Although the fibre was multimode at the pump wavelength, we were able, by careful alignment, to couple up to 300 mW into the sample in the fundamental mode, without exciting higher orders. A half-wave plate placed just before the coupling objective allowed us to rotate the input polarisation from parallel to perpendicular to the fibre flat side. For the coincidence measurement two InGaAs APDs biased above breakdown (photon counting mode) were spliced to a 3 dB fibre splitter, into which we launched the output from the sample. The coincidence curve was collected with a Modulation Domain Analyser (MDA) attached to Nuclear Instrumentation Module (NIM) discriminator connected to the detectors. The latter was used to reject noise-generated low amplitude pulses from the APDs, converting also their electric output to a standard TTL logic signal for further processing. For the QPM tuning curves collection the output from the fibre was launched into a Bentham grating monochromator and then into a single photon counting APD detector connected to a rate meter. In either configuration, a silicon filter, placed before the input lens to the detector pigtails, was used to suppress the pump radiation. The system was fully computer controlled, allowing the experiments to run unattended.

Fig.2 illustrates the coincidence curves collected with vertical (top) and horizontal (bottom) polarisation obtained for a pump wavelength of 766 nm, very close to the degeneracy point. The large background in the curve is due to the high dark counts rate ($\sim$ 200 kHz) of the InGaAs detectors, still at a developmental stage. Due to the tensorial nature of the nonlinear coefficient and to the fibre birefringence the vertical polarisation gives a larger signal. A Gaussian fit to the peak forthe vertical polarisation in Fig.2, allowed us to estimate a full width at half maximum (FWHM) $\simeq$ 3 ns, determined by the jitter in the detection system. As an additional result, given the measured coincidence rate $\sim$ 500 Hz, we were able to measure the quantum efficiencies of the two APDs to be $1.4 \pm 0.4\%$ and $1.7 \pm 0.4\%$ and to estimate the pair-photons production rate to be ~ 150 MHz. The latter can be compared to the theoretical value if we recall the expression for the fluorescence power at degeneracy, which, in low gain condition, reads:

$$P_s = \hbar\omega_s \, B_w \, \eta_{SH} \, P_{pump} \tag{1}$$

where we neglected pump depletion and signal and pump propagation losses. B_w is the signal linewidth, defined as the FWHM of the signal spectrum. In a second-order approximation, holding close to degeneracy, it is given by:

$$B_w = \sqrt{\frac{2\pi}{\left.\frac{\partial^2 \beta_s}{\partial \omega_s^2}\right|_{\omega_{s0}} L}} \tag{2}$$

where β_s represents the signal wave-vector.

The bandwidth was calculated to be 13 THz, therefore the expected pair-photon rate $(P_s/\hbar\omega_s)$ amounts to 156 MHz, in extremely good agreement with the measured value.

Fig.3 shows the collected QPM tuning curve. We could actually measure the signal branch, while, due to the roll-off in the detector sensitivity and the significant losses for long wavelengths in the sample, only three idler points could be identified experimentally. The other points on the idler branch, were calculated from the pump and signal wavelength. The bars correspond to the bandwidth for the process, which is also plotted, versus the signal wavelength, in Fig.4. We found a good qualitative agreement between the experimental and the theoretical values of the bandwidth.

We have reported on the observation of quasi-phase matched parametric fluorescence from periodically poled silica fibres. Using InGaAs APDs operated in photon counting mode we were able to measure the photon pair production rate to be 150 MHz for 300 mW of pump power at 766 nm. At the same time we measured the absolute quantum efficiency of our detectors, $\eta_1 = 1.4 \pm 0.4\%$ and $\eta_2 = 1.7 \pm 0.4\%$. Even higher pair production rates can be expected in the near future, if we remember that the effective nonlinear coefficient can be still improved 4-6 times. These results clearly show the large potential of periodically poled silica fibres as nonlinear media in all-fibre single photon sources, which are going to play a major role in the future for the implementation of quantum cryptography systems and as absolute metrology standards. In particular, to overcome the limitations imposed by the InGaAs photon counting APDs, still at a developmental stage, we shall look at a quantum key distribution system where the detector on the signal branch ($\lambda_s \simeq 900$ nm) is a much better performing silicon APD. This will allow us to increase the overall range and signal to noise ratio of the system.

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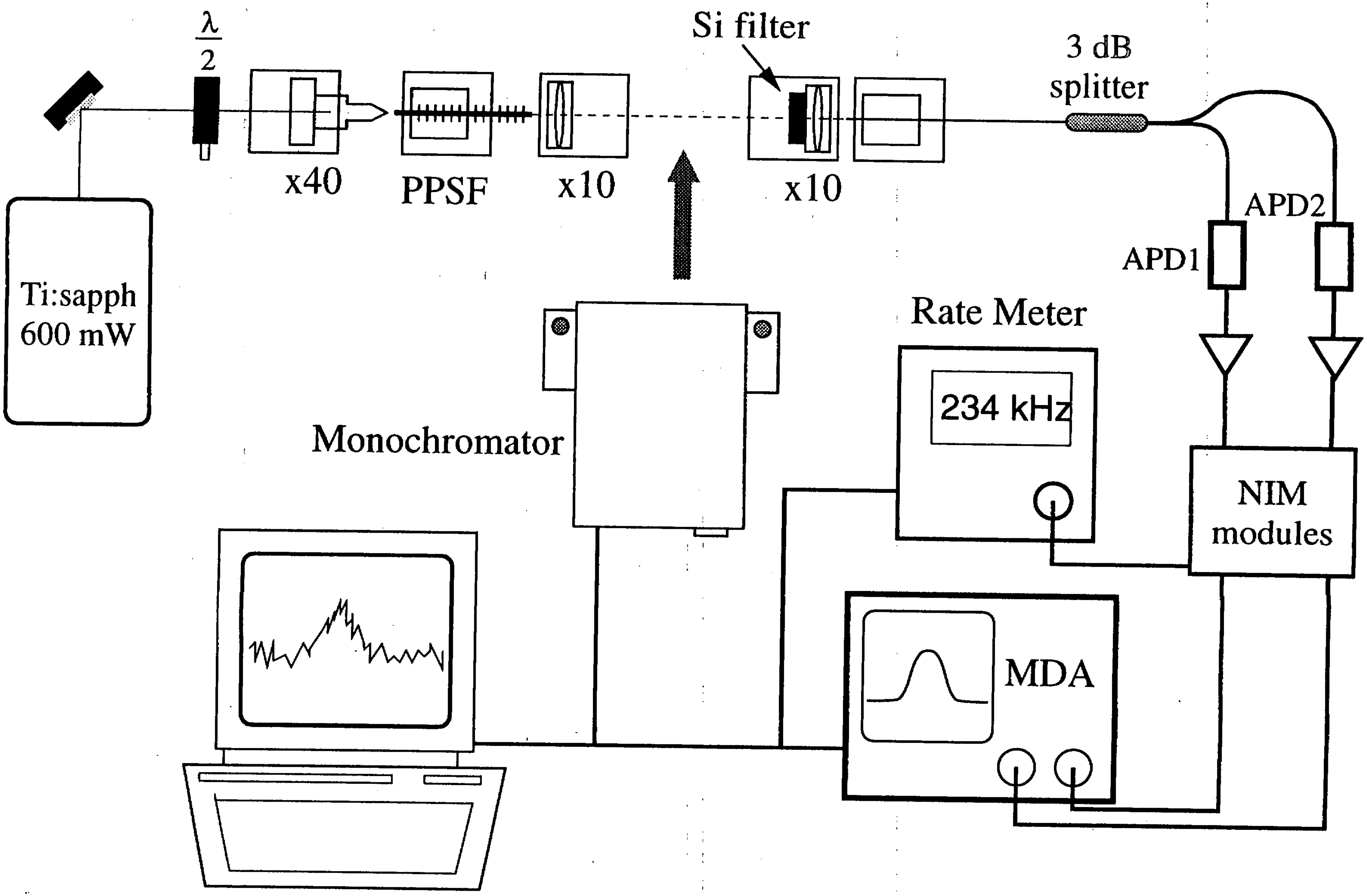
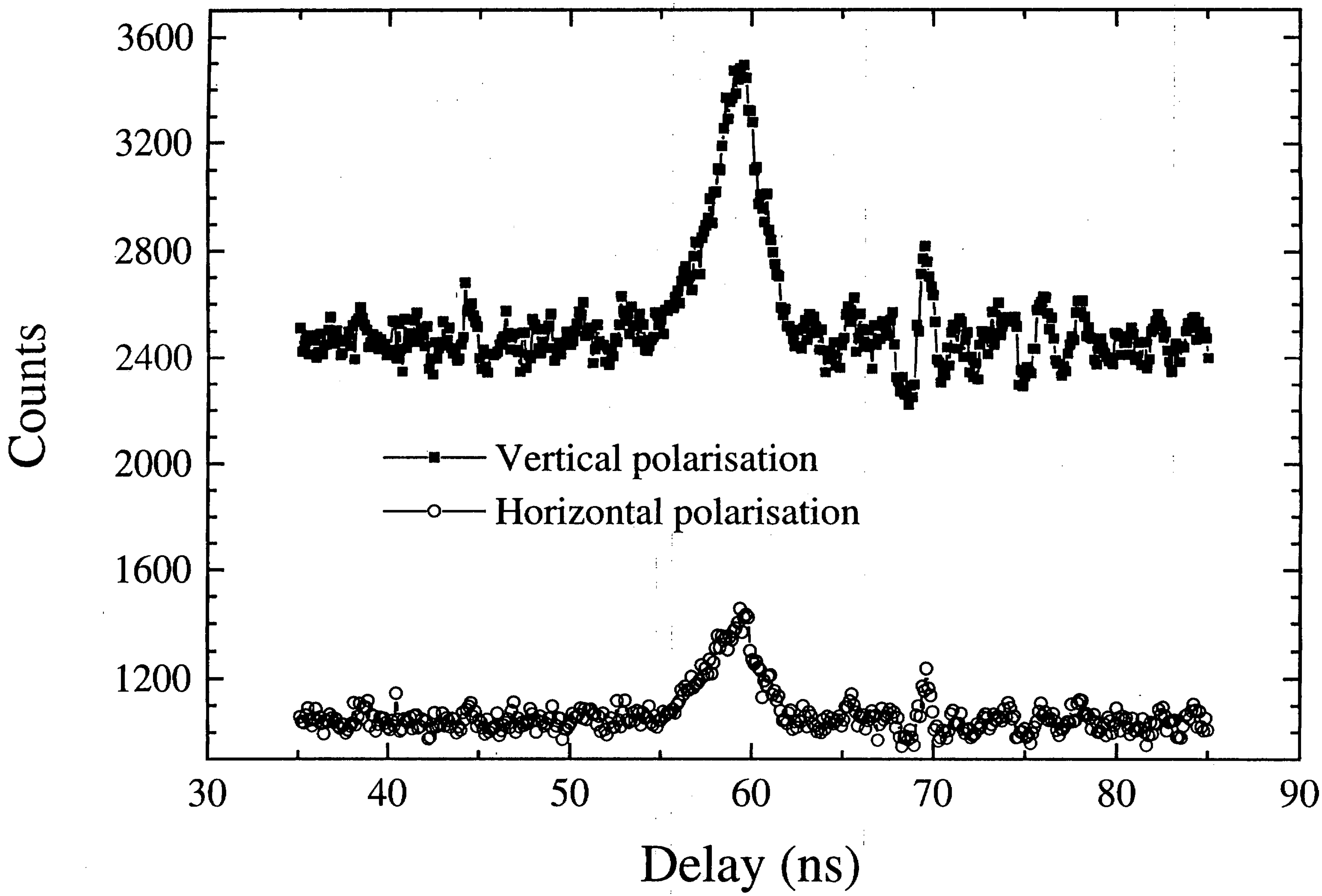
FIGURE CAPTIONS

- **Fig.1:** Setup for parametric fluorescence generation and coincidence measurement. In order to collect the fluorescence spectrum APD1 was disconnected from the splitter and used to detect the signal coming from the monochromator inserted after the first x10 objective.
  APD: Avalanche Photodiode, PPSF: Periodically Poled Silica Fibre, MDA: Modulation Domain Analyser, NIM: Nuclear Instrumentation Module.
- **Fig.2:** Coincidence curves for vertical (top) and horizontal (bottom) pump polarisation. The background is due to random coincidences generated by the detectors dark counts.
- **Fig.3:** QPM tuning curve. The bars show the measured signal bandwidth.
- **Fig.4:** Signal bandwidth versus signal wavelength. The bars show the error on the measured bandwidth. There is a significant qualitative agreement between theory and experiment.

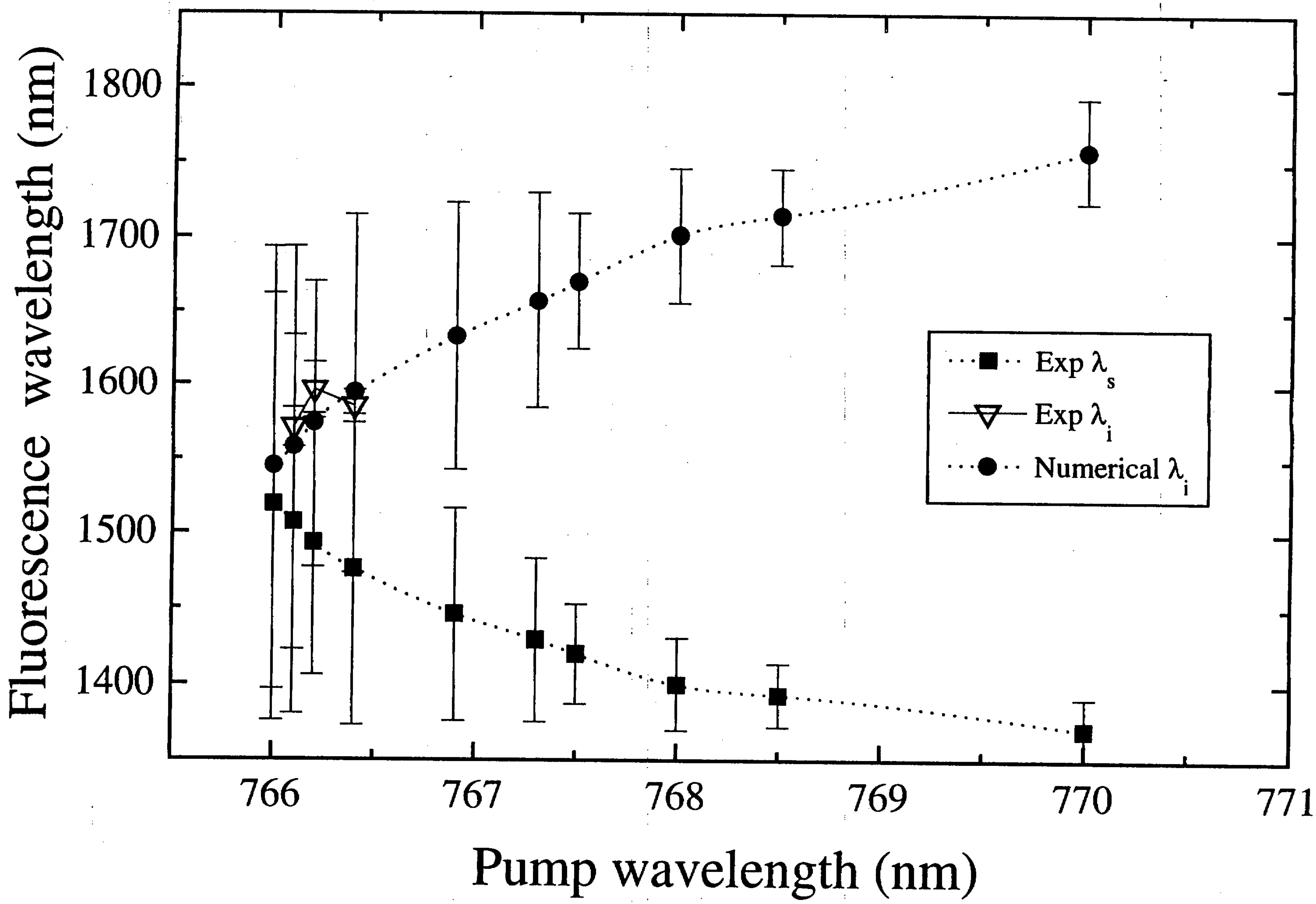
G. BONFRATE & AL FIG. 1



G. Bonfrate & al. Fig. 2



G. Bonfrate & al. Fig. 3



G. Bonfrate & al. Fig. 4