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Large Mode area fibres for high power applications

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Abstract

We review our recent work towards designing large mode area fibres for high power applications. We show that appropriately designed doped multi-mode fibres can be used to provide robust single mode output when used in fibre laser cavities. Single mode (SM) fibre mode field diameters of $\sim 35\,\mu$m are demonstrated as are record SM pulse energies of 0.5 mJ at 1550nm with a repetition rate of 200Hz. Energies approaching 1mJ are obtained with a slight compromise in mode quality. A slight modification in the laser cavity results in a passively modelocked laser giving femtosecond pulses with nJ energies.

1. Introduction

Fibre lasers are compact reliable optical sources for applications at eye-safe wavelengths around 1550 nm. For example fibre lasers are well suited to pumping nonlinear crystals such as periodically poled lithium niobate allowing for the development of widely wavelength tunable sources[1]. Previously much of the work on the development of erbium doped fibres, driven by the telecommunications industry, has concentrated on maximising the small signal optical gain, and optical gain efficiency of single transverse mode devices. This design objective restricts the energy storage of such fibres due to the rapid build up of amplified spontaneous emission (ASE) with increasing pump power and therefore limits the maximum energy that can be stored to $\sim 10\,\mu J$. Moreover, the fibre design optimisation results in such fibres having a small spot size so as to maximise the pump intensity[2]. Unfortunately, this thereby increases the strength of nonlinear interactions within the core and once again limits the energies/peak powers which may be generated within the fibre[3]. It is thus apparent that 'conventional' doped fibres are far from ideal for the amplification/generation of high energy/power optical pulses. Fortunately, however there is plenty of scope for improving the fibre design for these applications

The obvious way to simultaneously increase the energy storage and reduce the nonlinearity of single mode fibres is to increase the fibre mode area, (while ensuring that the guidance remains single moded at the operating wavelength). This reduces the intensity and thus the nonlinearity while the increased energy storage results from the resulting compromised gain efficiency. Recently we fabricated a high concentration erbium doped amplifier fibre with a simple low Numerical Aperture (NA) step index profile which has a mode field area (MFA) of $310\,\mu\mathrm{m}^2$ i.e. nearly an order of magnitude greater than conventional fibre designs[4]. This fibre, used as the last stage of an amplifier cascade gives amplified pulses energies $> 150\,\mu\mathrm{J}$ for nanosecond pulses (corresponding peak powers are $>$ 100kW)[5]. Incorporating this fibre into a simple Q-switch configuration gave pulse energies of $180\,\mu\mathrm{J}$ at a repetition rate of 200 Hz- a record for a fibre laser. The NA of this fibre ($\sim$ 0.006) is about as low as can reliably be achieved whilst maintaining robust single-mode guidance within the structure. Also the MFA was as large as we could tolerate in terms of bend loss – note that for any practical fibre device the fibre will have to be packaged with a maximum bend radius of $\sim$ 15 cm and thus we require that the bend loss with this radius was negligible. New fibre designs and concepts are thus required to further significantly increase the output pulse energies from such fibre laser systems.

Here we demonstrate that the low NA fibre concept extended to the case of multi-mode guidance can, with appropriate fibre design, be used to obtain robust single mode operation and increased output energy from a variety of fibre lasers. We obtain >0.5mJ SM output pulses from a Q-switched fibre laser and even higher pulse energies, (as high as 0.85mJ) with slightly compromised spatial mode quality. Using a passively modelocked soliton fibre laser configuration we generate nanojoule femtosecond laser pulses, confirming the expected relationship between the decrease in the effective nonlinearity and the energy needed to form a soliton in such a fibre[3].

2. Design and Fabrication of large area fibre cores

Scaling of the fibre MFA in single mode fibres is ultimately limited by two factors. Firstly, the accuracy with which one can reliably control the index difference between core and cladding and which defines the maximum core dimension that supports pure single mode guidance. (The minimum refractive index difference that can be precisely fabricated is $\sim 10^{-3}$). The second limit is imposed by the fibre bend loss which increases rapidly with increasing MFA. Therefore means for extending the core dimensions for which one can achieve single mode operation of an active device and ways of reducing the bend loss of large MFA fibres are critical to further scaling the power characteristics of fibre lasers.

The approach we have followed in this work is to move to a multimode, low NA fibre which is selectively doped with erbium to give preferential gain to the fundamental mode, such that when the fibre is used in a laser cavity only the fundamental mode is excited. This technique enables one to scale up the range of single mode MFAs achievable beyond the strictly single mode fibre guidance limit. Use of a low NA structure is important in that it reduces the total number of guided modes for a given core diameter which is important in terms of maximising energy storage within the amplifier, and in terms of maintaining robust single mode operation. In addition, we have incorporated an additional ring in the fibre refractive index profile to reduce the fibre bend loss, and ensured that the fibre outer diameter is sufficiently large to limit the effects of mode coupling within the structure over length scales of the order of a typical active device length ($\sim$ 10m).

A simplified version of our fibre refractive index profile is shown in Fig 1a. The refractive index profile consists of a raised index core of low NA (solid line), similar to the profile of previously fabricated low NA fibres, and an outer ring of raised index (dashed line). Guidance in the fibre is purely single mode for a core radius of $< 5\ \mu$m, the second and third mode cut-offs occur for core radii of 7.9μ m and $10.4\ \mu$ m respectively. We first consider only the linear guidance properties of the fundamental mode within the fibre. Parts (b)-(c) of figure 1 show how the addition of this ring influences the spot size and bend loss as a function of core size (defined as the radius of the inner core).

It is clear that the outer ring not only broadens the field significantly, but also it reduces the sensitivity of the mode field diameter to variations in the core radius. Most significantly it also reduces the bend loss (by as much as 10dB for a core radius $\approx 10\mu$m and > 40 dB for a core radius of $5\mu m$).

The fiber is doped with erbium ions only within the inner core such that the overlap of the doped region is greater for the fundamental mode than any other guided mode of the system (see Fig. 2), so that this mode will see the largest gain when the fibre is pumped. This provides the mechanism for selective excitation of a single mode of the system when the fibre is placed in a laser resonator.

Based on these consideration a suitable preform was fabricated. Its refractive index profile is shown in Fig. 2 (solid line) where it has been scaled down to a fibre core diameter of 21 μm The erbium ions were only incorporated into the inner core region with a nominal erbium concentration of 400ppm. The predicted bend loss of our fibre is < 0.1dB/m for a 30cm bend radius. The majority of our experiments herein were performed with a fibre pulled from this preform with an inner core diameter 21μm and corresponding fibre outer diameter 235μm, although an additional short section of fibre from the same preform with a core diameter of 27μm was also tested. Superposed on Fig. 2 are plots of the field distributions of the first and second order mode for the 21μm-core structure. (Additional weakly guided modes associated with the outer ring structure are predicted but these modes are so sensitive to bend loss that they can be ignored). From these plots it can be seen that there is a significant difference between the fundamental and second-order mode in their overlap with the doped inner core region. As discussed previously this results in a significant gain differential between the two modes and preferential excitation of the fundamental mode. Moreover, mode coupling between the fundamental and higher order modes is low due to the large fibre outer diameters[6,7], allowing for single-mode output even in the ~10m long cavities reported herein. These fibres were then incorporated in simple laser cavities which are described below to demonstrate the advantages of these fibre designs both from an energy storage and nonlinear perspective.

3. Q-switched fibre lasers

Due to the enhanced energy storage capacity of large mode area (LMA) fibres they are ideally suited for Q-switching where, as we show below, they perform with extremely high efficiency providing record pulse energies for such a fibre system. The Q-switch laser configuration is shown in Fig. 3. The cavity comprises a length of LMA erbium doped fibre, an intracavity lens, an acousto-optic Bragg cell and a mirror with high reflectivity across the full erbium band. The cavity is defined by the 4% Fresnel reflection from the cleaved fibre launch end and the HR mirror which is aligned to reflect first-order diffracted light back into the cavity. The fibre was pumped with up to 2.5W of 980nm radiation from a Ti:Sapphire laser launched into the fibre through a 980/1550nm dichroic mirror. The maximum launch efficiency into the fibre was ~70%. The output laser radiation was separated from the incoming pump radiation by the dichroic beam-splitter.

First we investigated the 21μm-core fibre. The laser was characterized for a number of fibre lengths under Q-switched operation to determine the maximum pulse energy and time-averaged output power achievable from the fibre. Maximum average output powers were achieved for a cavity length of 8m. In this instance the laser threshold occurred at ~900mW of incident pump. The average slope efficiency was ~50% with respect to launched pump corresponding to an estimated quantum slope efficiency ~75% indicating that despite the unusual design the fibre is still highly efficient. Laser output powers well in excess of 500mW were achieved for Q-switching at high repetition rates(>1.5kHz) The maximum pulse energy for this fibre length was ~0.4mJ, obtained at repetition rates below 500Hz. The laser operated at 1558nm. The minimum pulse duration was 40ns giving a maximum pulse peak power of 10kW, which we believe to be a record for Q-switched fibre lasers.

Maximum pulse energies were obtained for a fibre length of 12m. Fig. 4 shows the output pulse energy versus pulse repetition frequency for this length. At repetition frequencies <200Hz pulse energies in excess of 0.5mJ are obtained. The pulse energies at low repetition rates were measured in three different ways to confirm the results obtained. Firstly, we measured the average power and, from a study of the temporal laser dynamics between pulses, made a correction for the ASE emitted during the gain recovery stage. Secondly, we used average power measurements but made the ASE correction based on time average spectral measurements of the laser output. Finally, we made direct pulse energy (pulse height) measurements on a calibrated fast detector (requiring no ASE correction). For the highest pulse energy we report the average output power at 200Hz was 134mW. The average ASE power from the laser-output with the Q-switch turned off was 37mW. The contribution of ASE to the total recorded signal power during Q-switching at 200Hz was estimated at 31mW using method 1 and 28mW using method 2, resulting pulse energy estimates of 0.514 and 0.527mJ for methods 1 and 2 respectively. The direct pulse energy measurements gave a value of ~0.52mJ yielding an average value for our measurements of ~0.52mJ.

In Fig. 4 we also plot the variation of pulse width with pulse repetition frequency. As expected the pulse width decreases with reduced repetition rate and correspondingly increased energy. The hump in the curve indicates a pulse shape change (formation of distinct side-lobes) which occurs below ~800Hz. The pulse width of the 0.52mJ pulses was 70ns, corresponding to a peak power of ~7kW. The spectral bandwidth of these pulses was ~10nm and reduced rapidly with increasing repetition rate. Bandwidths as narrow as 0.1nm could be obtained for pulse energies as high as 0.250mJ by incorporating a narrowband optical filter within the cavity.

The beam propagation parameter (M^2) of the output laser beam was measured using a commercial beamscope (Merchantek Beamscope). The measurements of the 21 micron core fibre yielded values of 1.1 and 1.2 for the two orthogonal, transverse spatial co-ordinates, confirming the high quality, SM nature of the beam. The fundamental mode field diameter (MFD) was measured by a scanning knife edge technique whereby the divergence was recorded as a function of the distance from the fibre end. These results are shown in Fig. 5 along with the measured beam profile. This divergence was used (in combination with the measured M^2 value) to calculate the fibre MFD. This gave a MFD of 34μm for the 21 μm fibre. The mode area of this fibre is thus estimated at $\sim 910\mu m^2$ approximately 20-30 times that of conventional erbium doped fibres, and around three times bigger than we had previously achieved in a strictly SM system.

We next investigated the 27μm-core fibre (outer diameter: 300μm). Theoretically, we estimated the fibre to guide 3-4 core modes. We optimized the cavity length for maximum pulse energy. In Fig. 6 we plot pulse energy versus repetition frequency for a fibre length of 9m. We obtain pulse energies as high as 0.83mJ at repetition rates below 100Hz (evaluated as previously for the 21μm fibre). The duration of these pulses was 80ns and their corresponding peak power ~10kW. A plot of the scanned intensity mode profile is presented inset in Fig. 6, showing a reasonably Gaussian profile, although it was fairly elliptic. This observation was confirmed by M^2 measurements which gave values of 2.0 and 1.3 for the two ellipse axes. The mode quality is thus slightly degraded in this more highly multi-moded structure, presumably by mode-coupling. Although not measured, we estimate an MFD for the fundamental mode well in excess of 40μm.

4. Passive Mode-locking of LMA fibres

It should be noted that the Q-switching configuration used in Section 3 is almost identical to that of a frequency shifted passively mode locked fibre laser[8,9]. The only difference is that in a Q-switching configuration the AOM is turned off and on periodically while for passively modelocking it is run continuously acting as a frequency shifter. Thus we were able to examine the performance of these fibres in a passively modelocked cavity as well.

This simple configuration results in a high power femtosecond laser with excellent pulse characteristics. Importantly the output from the laser was robustly single-moded and in addition the output pulses provide a useful diagnostic of various important fibre parameters such as the dispersion and mode-area.

The actual laser cavity we used differed slightly from that shown in Fig. 3 and is shown in Fig. 7. The only difference is the presence of additional polarisation optics in the cavity. The presence of the frequency shifter in the cavity ensures that any CW radiation is eventually shifted outside the erbium gain bandwidth of the cavity and decays away. In contrast high intensity pulses nonlinearly generate new frequencies during each round trip ensuring that the central frequency of the pulses remains within the gain bandwidth of the medium allowing stable operation[3,9]. This form of mode-locking is well known and is quite similar to the idea of "sliding guiding filters" common in soliton transmission lines[10]. Once mode-locked the repetition rate was 10.5MHz corresponding to a fibre length of 14 metres. The polarisation optics in the cavity are not necessary for mode-locking but instead act to shorten the mode-locked pulses through nonlinear polarisation evolution[9].

As is common to frequency shifting lasers this device operated in a number of output modes[9]. At high incident powers the laser would usually self-start mode-locking although at lower powers it required some perturbation (typically we would tap the optical bench in order to get it to start). Upon mode-locking neither the average power nor the mode-profile changed significantly. At the powers required for self-starting the laser was unstable with multiple pulses in the cavity and to obtain stable output the pump power was reduced until there was only a single pulse in the cavity.

When mode-locked the output pulse shape was either a long square pulse with a width between 20 – 30 ps or a much shorter sech shaped pulse. A typical autocorrelation and spectrum of a "long" pulse is shown in Fig. 8, the pulses are 20 ps long with a spectral width of 0.12 nm and a pulse energy of 20nJ. These relatively long pulse were obtained without the polarisation optics in the cavity. Such long square pulses are to be expected in frequency shifted lasers[9]. The pulse energy is we believe a record for a passively mode-locked fibre laser and is due to the decrease in the effective nonlinearity caused by the large mode area.

The second distinct mode-locking regime is shown in Fig. 9. Here the pulse is 900fs (without polarisation control it broadens to 4ps) and is near transform limited with a spectral width of 2.8 nm. The measured average pulse power is 16mW giving a pulse energy of $\sim$ 1.6nJ and a peak power of 1.7kW. The pulse energy is comparable to that obtained from stretched pulse lasers. The sidelobes on the pulse's spectrum (see insert in Fig. 9) are common to these soliton lasers and from their spacing it is possible to estimate the fibre dispersion[11,12] as $\approx$ 20 ps/(nm.km) with is approximately that of fused silica as expected from the fibre design. From these pulse and fibre parameters we estimate the soliton order to be 1.8 at the laser output. For comparison the fundamental soliton energy in a conventional doped fibre with the same dispersion would be $\approx$ 20 pJ.

5. Conclusions

In this paper we have demonstrated that it is possible to use low NA multimode fibre to achieve significant increases in both energies and MFA from single mode ouput fibre devices. Use of a low index ring is also shown to reduce the bend loss of the fundamental mode in such fibres. Employing this approach we have obtained record pulse energies from a fibre system. With an optimized fibre design use of these concepts should permit the development of mJ fibre laser/amplifier systems. In addition we, have demonstrated the benefits of the associated reduced nonlinearity of such LMA fibres in a soliton laser obtaining nJ energies for fs pulses. This opens the way to $\sim$100nJ short pulse systems using more complex cavity designs. It should also be noted that the design presented is fully compatible with the cladding pumping concept[13] facilitating the development of higher average power (multi-10W), mJ systems.

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FIGURES

Fig. 1. Theoretical model of the refractive index profile showing the advantages of using a raised outer ring. Fig. (a) shows the simplified theoretical model of the refractive index profile. The dashed section is the raised outer ring. Fig.(b) shows how the spot size diameter of the fundamental mode at 1550nm varies with the core radius – the solid line corresponds to the solid profile in Fig. (a) while the dashed line shows the effect of the outer ring. Similarly Fig. (c) shows the effect of the outer ring on the bend loss for the fundamental mode at 1550nm for a 30cm bend radius.

Fig. 2. Measured Refractive Index profile of the fibre preform (solid line). Only the inner core ($-11\,\mu$m to $11\,\mu$m) is doped with erbium as explained in the text. The dashed line is the corresponding fundamental mode while the dot-dash line is the 2nd order mode.

Fig. 3. Schematic of the laser cavity for Q-switching.

Fig. 4. Pulse energy (solid line with circles) and pulse width (dotted line with squares) as a function of repetition rate for the 21μm-core fibre

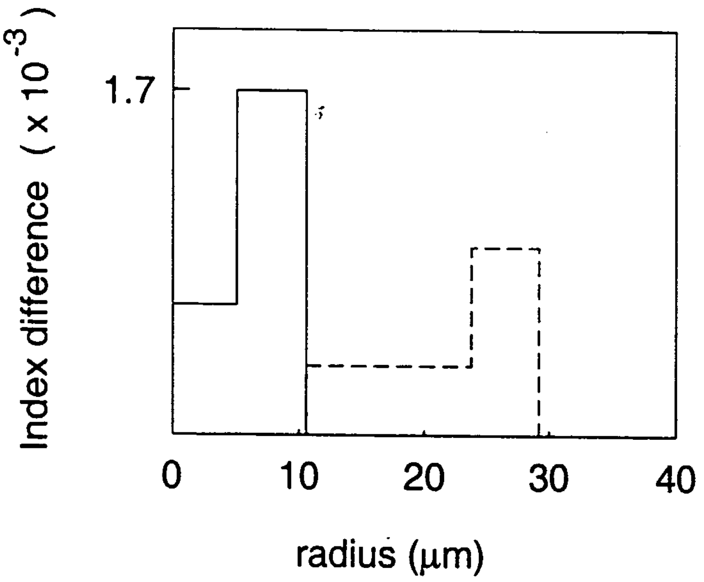
Fig. 5. Waistsize measurements as a function of distance for the 21 micron core fibre. The slope of the line is 0.279. The insert shows the beam profile in the transverse direction.

Fig. 6. Pulse energy versus repetition rate for the 27μm-core fibre. The inset shows a slit scan of the intensity profile and the M^2 values.

Fig. 7. Schematic of the laser cavity for passive mode-locking. WP1: $\lambda/2$ waveplate, WP2: $\lambda/4$ waveplate, FS: Frequency Shifter, POL: Polariser, L1: Lens, M1: dichroic mirror. See text for more details.

Fig. 8. Pulse autocorrelation and spectrum for long (20ps) square pulses with a energy of 20nJ. The insert shows the pulse spectrum.

Fig. 9. Pulse autocorrelation and spectrum for short soliton pulses. The spectra shows distinctive sidelobes common to soliton lasers. The pulse width is 900 fs with a bandwidth of 2.48 nm.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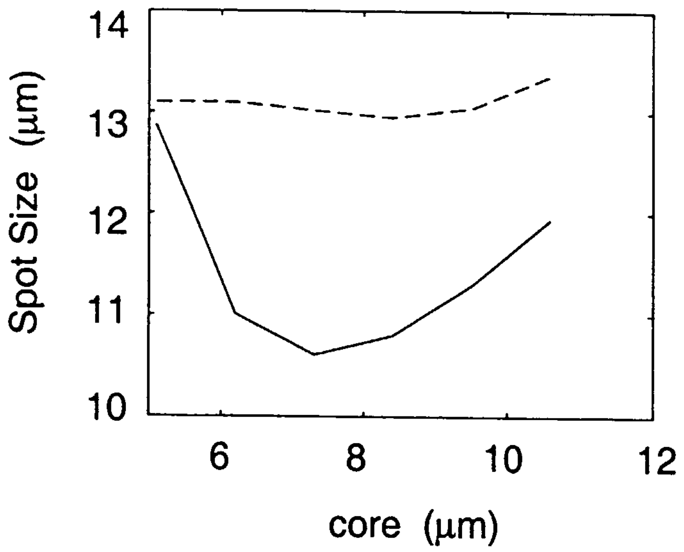
10
20
30
40
radius (μm)


14
13
12
11
10
Spot Size (µm)
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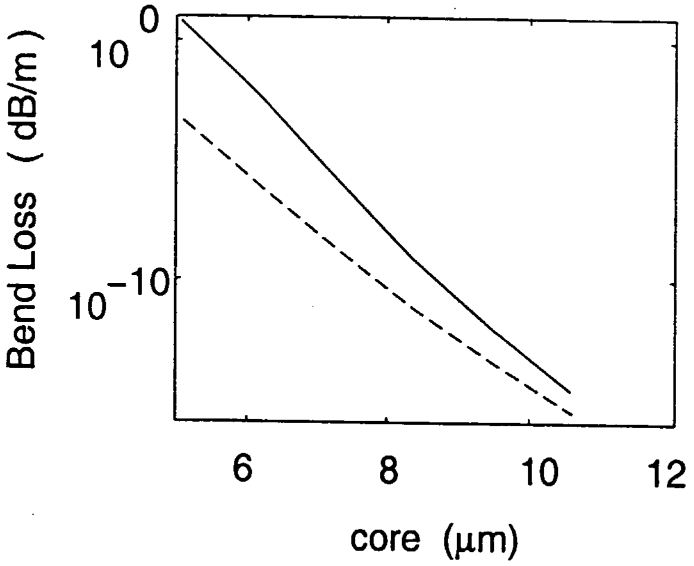
8
10
12
core (µm)



10^0
10^{-10}
Bend Loss (dB/m)
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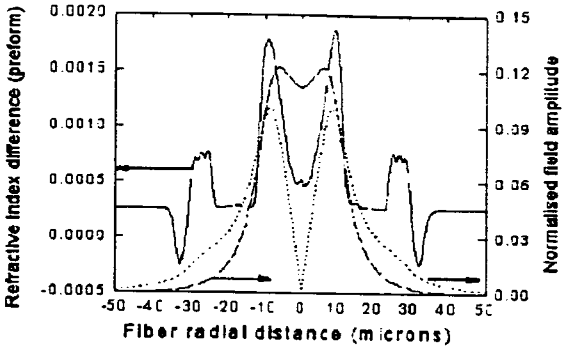
8
10
12
core (μm)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0.0010
0.0005
0.0000
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-40
-30
-20
-10
0
10
20
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40
50
Fiber radial distance (microns)
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0.06
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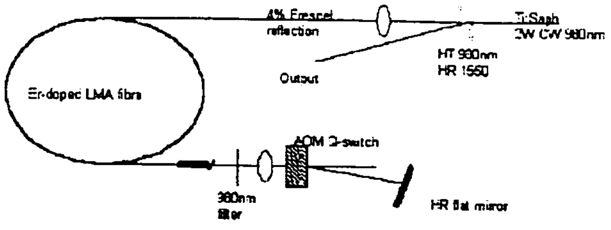
Normalised field amplitude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HT 980nm
HR 1550
Output
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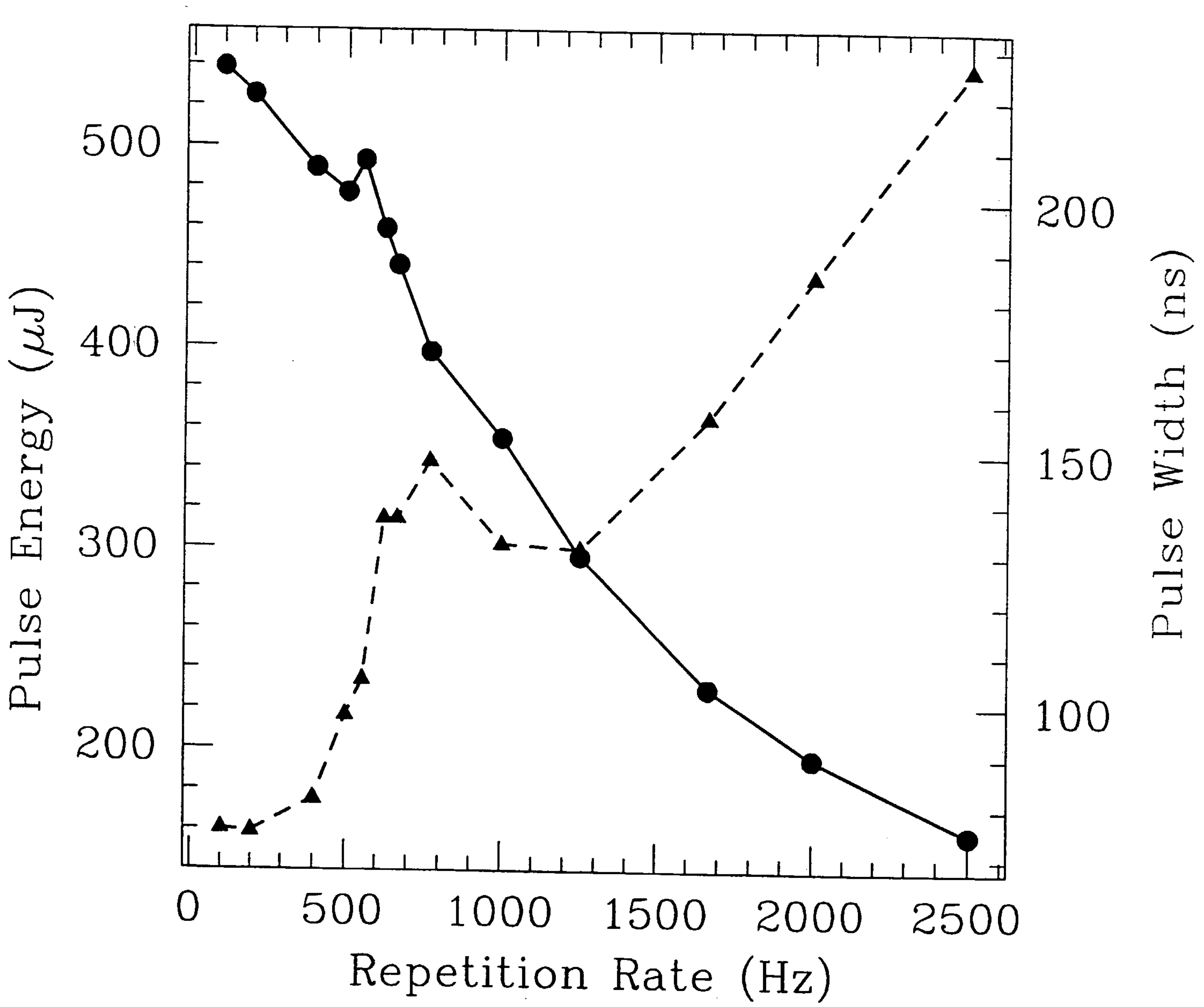
AOM Q-switch
980nm
filter
HR flat miror


Pulse Energy (μJ)
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200
Pulse Width (ns)
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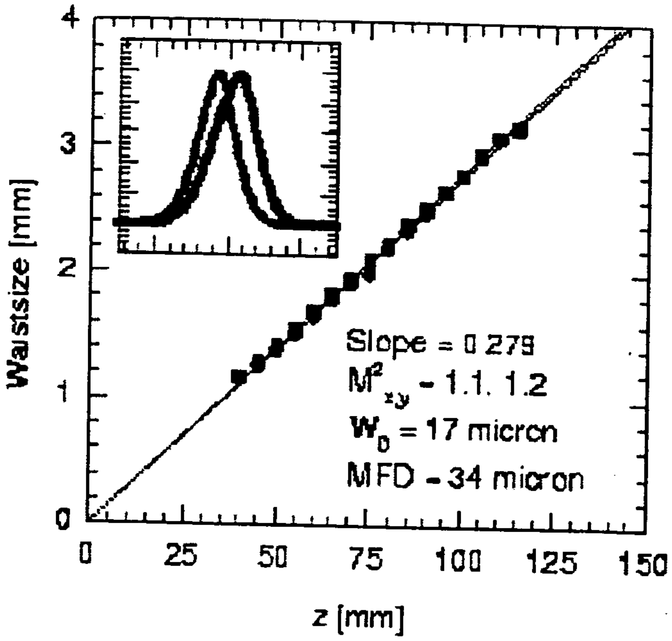
100
0
500
1000
1500
2000
2500
Repetition Rate (Hz)


Waistsize [mm]
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1
2
3
4
0
25
50
75
100
125
150
z [mm]
Slope = 0.279
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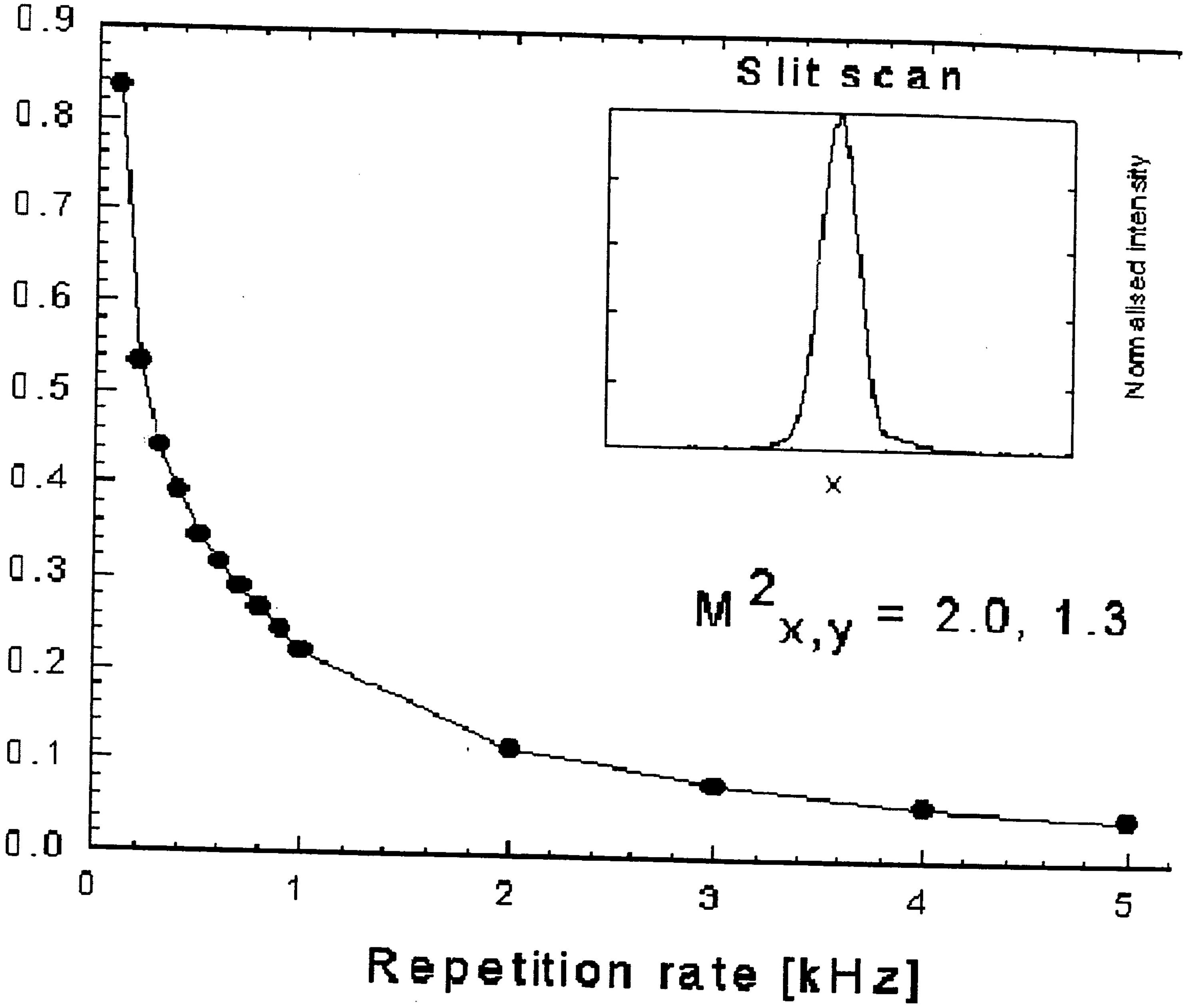
W_0 = 17 micron
MFD - 34 micron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0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
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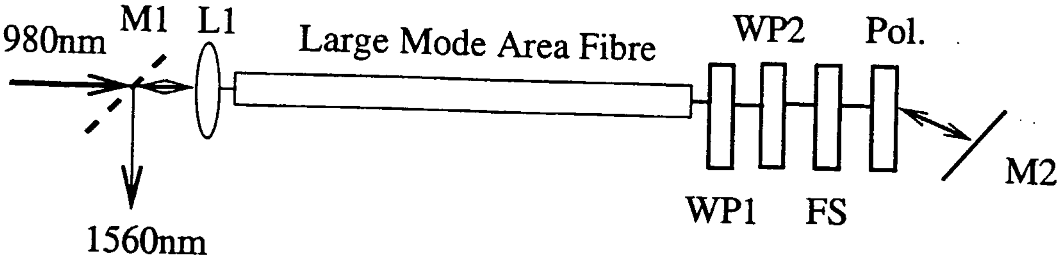
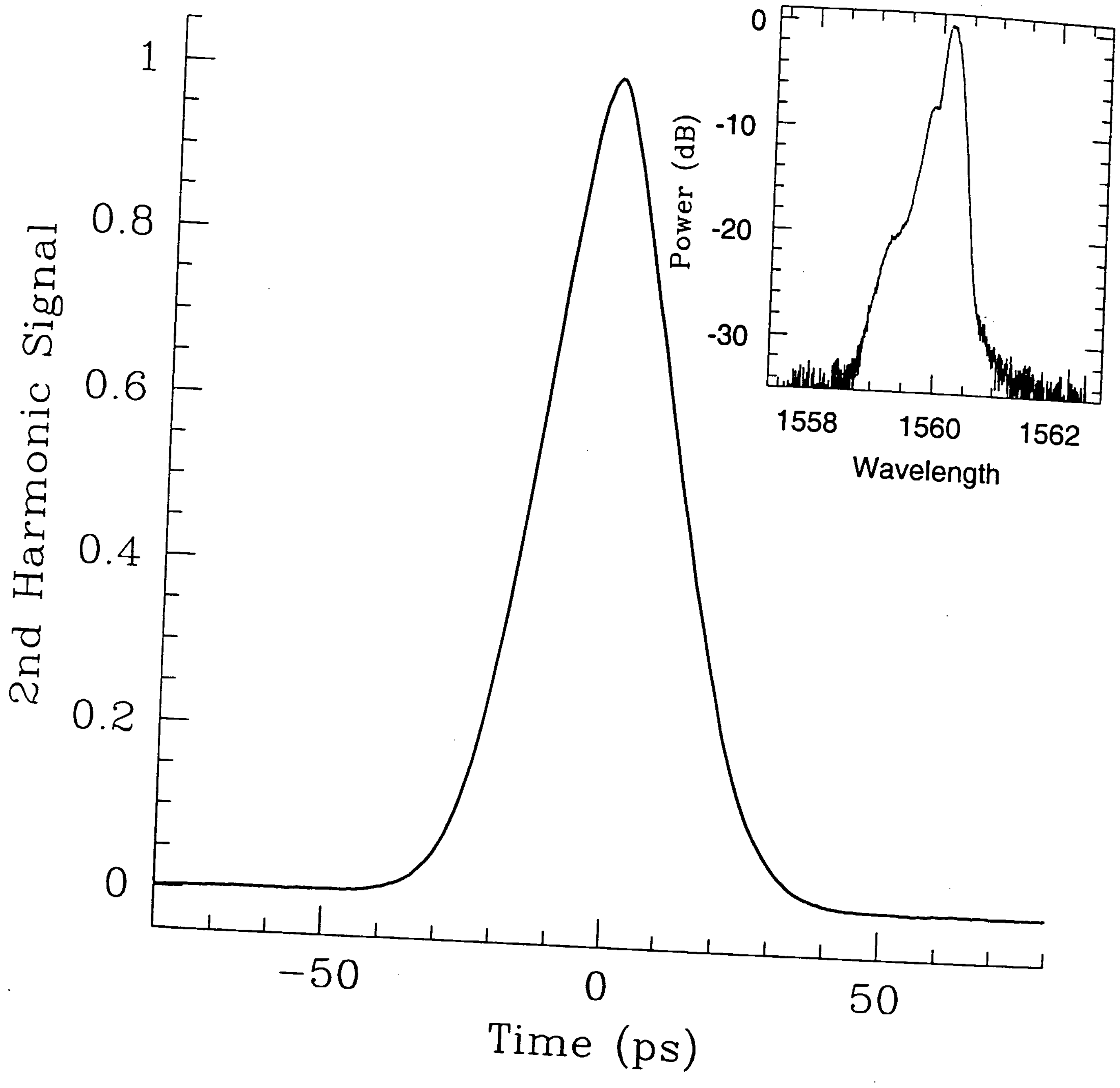
4
5
Repetition rate [kHz]
Slit scan
Normalised intensity
x
$M^2_{x,y}$ = 2.0, 1.3


980nm
M1
L1
Large Mode Area Fibre
WP2
Pol.
M2
WP1
FS
1560nm


2nd Harmonic Signal
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0.4
0.6
0.8
1
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0
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Power (dB)
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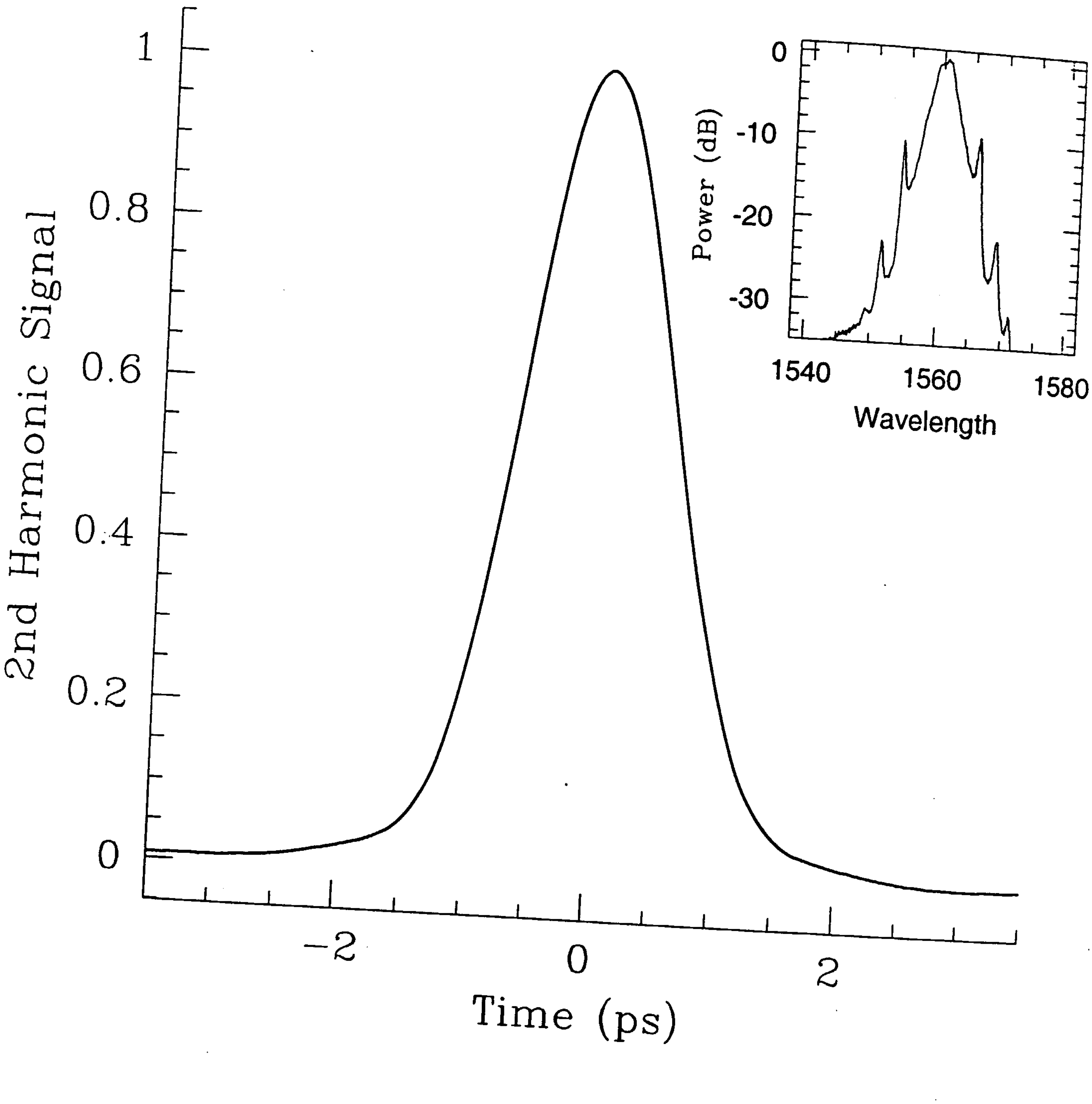
-20
-30
1558
1560
1562
Wavelength


2nd Harmonic Signal
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0
2
Time (ps)
Power (dB)
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-30
1540
1560
1580
Wavelength