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High phase conjugate reflectivity (>800%) by degenerate four-wave mixing in a continuous wave diode side-pumped Nd:YVO_4 amplifier

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Abstract

High phase conjugate reflectivities of > 800% have been achieved via degenerate four wave mixing in a continuous-wave diode side pumped Nd:YVO_4 amplifier. Reflectivity curves are shown as a function of input pump beam intensity, for three values of small signal amplifier gain, and comparison is made with numerical simulation.

Phase conjugation in gain media shows considerable promise as a practical method for the correction of beam distortions caused mainly by thermal lensing in intensively pumped laser amplifiers [1-4] as well as spectral and temporal control of the emitted laser radiation. Operation of such adaptive laser resonators using gain gratings has been successfully demonstrated in several solid state laser systems including flashlamp-pumped and quasi-cw pumped Nd-doped amplifiers [1,2], in laser pumped titanium-doped sapphire [4] and CO_2 lasers [5]. Extension of resonator operation to include continuous wave diode pumping would be the final step towards the generation of fully c.w. high power, ideally diffraction limited laser beam performance. For c.w. operation large values of small signal gains are required and so both a very efficient amplifier host, and carefully designed pumping geometries should be used for such an application. Four wave mixing experiments have already been performed in the c.w. regime using Nd:YVO_4 in a longitudinally pumped configuration, but low phase conjugate reflectivity of ~30%-50% was obtained, due to poor overlap of the interacting beams [6].

In this paper we demonstrate a very efficient Nd:YVO_4 c.w. side diode-pumped amplifier which exhibits phase conjugate reflectivities of > 800%, in a degenerate four wave mixing arrangement. The long path length of the interacting beams inside the gain medium enables generation of very high net single pass gain. We have measured gains of >5000, and inferred a small signal gain of ~7000 which allows such reflectivities of much greater than unity.

The gain medium used for the four wave mixing experiment was a 1.1 at.% Nd doped YVO_4 a-cut crystal of dimensions 20x3x5 mm^3 (CASIX, China), side pumped by a 20 W laser diode bar equipped with a fibre lens, which was able to deliver a collimated beam of 18 W, at a wavelength of 808 nm. The crystal was antireflection coated for the pumping wavelength on both b-sides while the a-sides were antireflection coated (R<0.1%) for 1064 nm. The output of the diode bar was subsequently focused using a cylindrical lens of focal length f=12 mm onto the b-side of the Nd:YVO_4 amplifier with the polarization of the pump beam rotated using a $\lambda/2$ waveplate, to be parallel with the c-axis of the crystal, thereby accessing maximum pump absorption (α=30 cm^{-1}) [7].

A single longitudinal mode Nd:YVO_4 laser, producing a diffraction limited beam of 300 mW output power at 1064 nm, was used to provide the forward pump (FP), backward pump (BP) and signal (S) beams for the four wave mixing experiment. The experimental arrangement used is outlined in figure 1. In order to achieve a more uniform gain across the beam profile, all beams were reflected on the b-side (pumping side) of the crystal [8]. The signal, forward pump and backward pump beams were all focused inside the crystal to a calculated spot size of 38 μm and the beams arranged to overlap at the focal point of the lens. The angle between the signal and forward pump beams was ~7 degrees while the angle between signal and a-axis was ~4 degrees. In the typical four wave mixing arrangement shown in figure 1, the backward pump beam is arranged to counter propagate with respect to the forward pump beam and the phase conjugate beam is detected via the beam splitter BS3.

Because of the intrinsic gain nonuniformity, due to the angle between pump and signal beams, the input power ratio of the interacting beams was adjusted empirically to achieve maximum phase conjugate reflectivity: the optimum power ratios between the interacting beams were BP:FP:S=17.6:11:1. All the interacting beams were polarized parallel to the c-axis of the YVO_4

crystal. The crystal orientation and the beam polarizations are shown in fig. 2a.

Figure 3 shows the experimental results of the phase conjugate reflectivity as a function of the forward pump intensity normalized to the saturation intensity (~1KW/cm^2) for three pumping levels of the amplifier. A maximum reflectivity of 8.2 was observed for a small signal gain (G_{sig}) of 1000. At each of the pumping levels the small signal gain seen by the signal beam (G_{sig}) is higher than that of the pump beam (G_{pump}) due to the angular dependence of the gain.

The four-wave mixing (FWM) interaction in the Nd:YVO$_4$ amplifier was modelled numerically. A complexity arises in the modelling since the small-signal gain is a function of the angle of the input beams. Pump and signal beams therefore experience different gains since they travel unequal path-lengths inside the gain volume and also due to incomplete spatial overlap with each other. The effective FWM region, where the beams spatially overlap, has a length that is necessarily shorter than the full gain length, and there are additional regions where the non-overlapping pump and signal beams separately experience different gain. We have attempted to incorporate these features by modelling the interaction as five distinct, but inter-linked, regions as illustrated schematically in Figure 2b. There is a central region in which FWM numerical modelling is performed using coupled nonlinear equations [9] describing a continuous-wave gain FWM interaction. We also model four separate additional gain regions, placed symmetrically on each side of the FWM region which provide saturable gain for the pump and signal beams.

For completeness, in our model, we have included the effect of standing wave gratings between pairs of counter-propagating beams (forward and backward pump beams and signal and conjugate beams) in these amplifier regions. To partition the gain between the different interaction regions, we have theoretically analysed the beam overlap geometry and incorporated the exponential absorption of the diode pumping beam. The experimental angular dependence of the small-signal gain used in conjunction with the analysis is consistent with an absorption depth of~300 μm for the diode pump light which itself corresponds well with the value of absorption coefficient of 1.1 at.% Nd:YVO_4 ~ 30cm^{-1} [7]. The crossing angle of the pump and signal beam together with their beam size and knowledge of the gain distribution allows us to estimate that the FWM region is approximately 20% of the gain-length seen by the signal beam. The small-signal gains in the amplifier regions were then determined such that the sum of the gains in the amplifier and FWM regions seen by either the signal or pump beams were equal to the experimentally measured small-signal gain. Hence the two amplifier regions traversed by the pump were given lower gain than the amplifier regions traversed by the signal to correspond with the experiment.

The results of the numerical simulations are shown as the curves in Figure 3. The theoretical results match the experimental data quite well both in terms of the absolute maximum reflectivity and the pump beam intensity at which the peak occurs. As a comparison we also ran the modelling as a simple FWM interaction, by assuming complete overlap of the beams and taking an average gain, intermediate to that seen by pump and signal beams. The results in this case were a much poorer match with experiment, predicting peak reflectivity occurring at pump intensity an order of magnitude lower than the one observed experimentally.

In conclusion, phase conjugate reflectivities higher than 800% were observed by degenerate four wave mixing in a gain saturated Nd:YVO_4 amplifier side-pumped by a continuous wave laser diode bar. The four wave mixing process has been modelled and the numerical results proved to be in good agreement with the experimental ones. Finally the high phase conjugate reflectivities observed should lead to the realization of a c.w. adaptive laser resonator using a Nd:YVO_4 crystal as the phase conjugate gain element and work is currently in progress to this end.

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Figure captions

Figure 1. a) Schematic of the degenerate four wave mixing arrangement used for the phase conjugate reflectivity measurements: BS# : beam splitter, HWP#: Half wave plate, FI: Faraday isolator, S: Signal beam, FP: Forward pump, BP: Backward pump, PC: Phase conjugate.

Figure 2. a) Schematic of the four wave mixing arrangement indicating the polarization of the interaction beams (FP:forward pump, BP: backward pump, S: signal, PC: phase conjugate) and the orientation of the Nd:YVO_4 crystal. The length of the crystal L=20 mm and the width d=5mm. b) Schematic of the equivalent gain model showing the separate four wave mixing and amplification regions.

Figure 3 Phase conjugate reflectivity versus intensity normalized to I_{sat} (~1KW/cm^2) for various values of small signal gain (i) G_{sig}=1000, G_{pump}=100, (ii) G_{sig}=150, G_{pump}=40, (iii) G_{sig}=45, G_{pump}=20. The points represent experimental values while the lines represents the numerical modeling results.

Fig 1

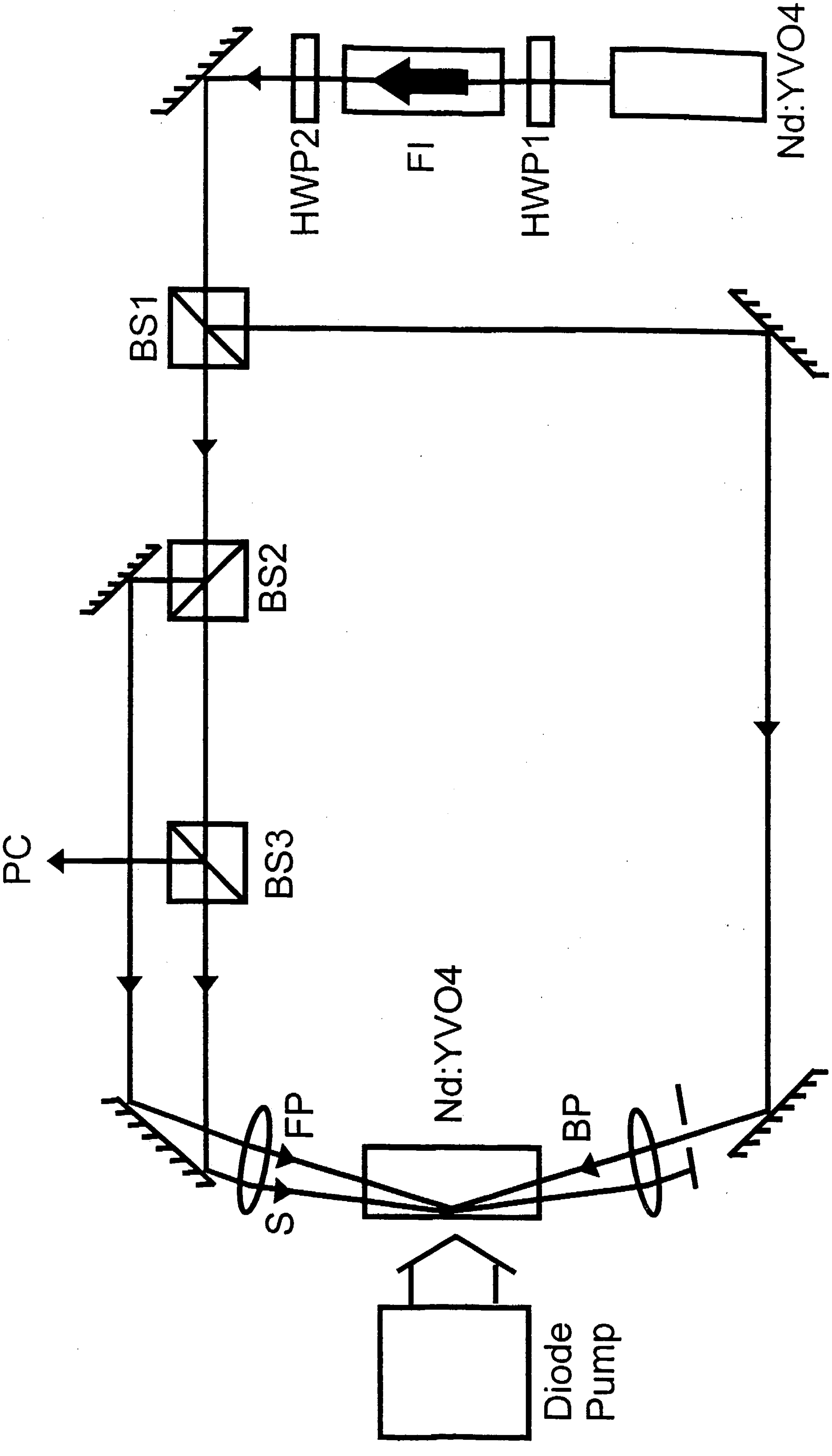


Fig 2

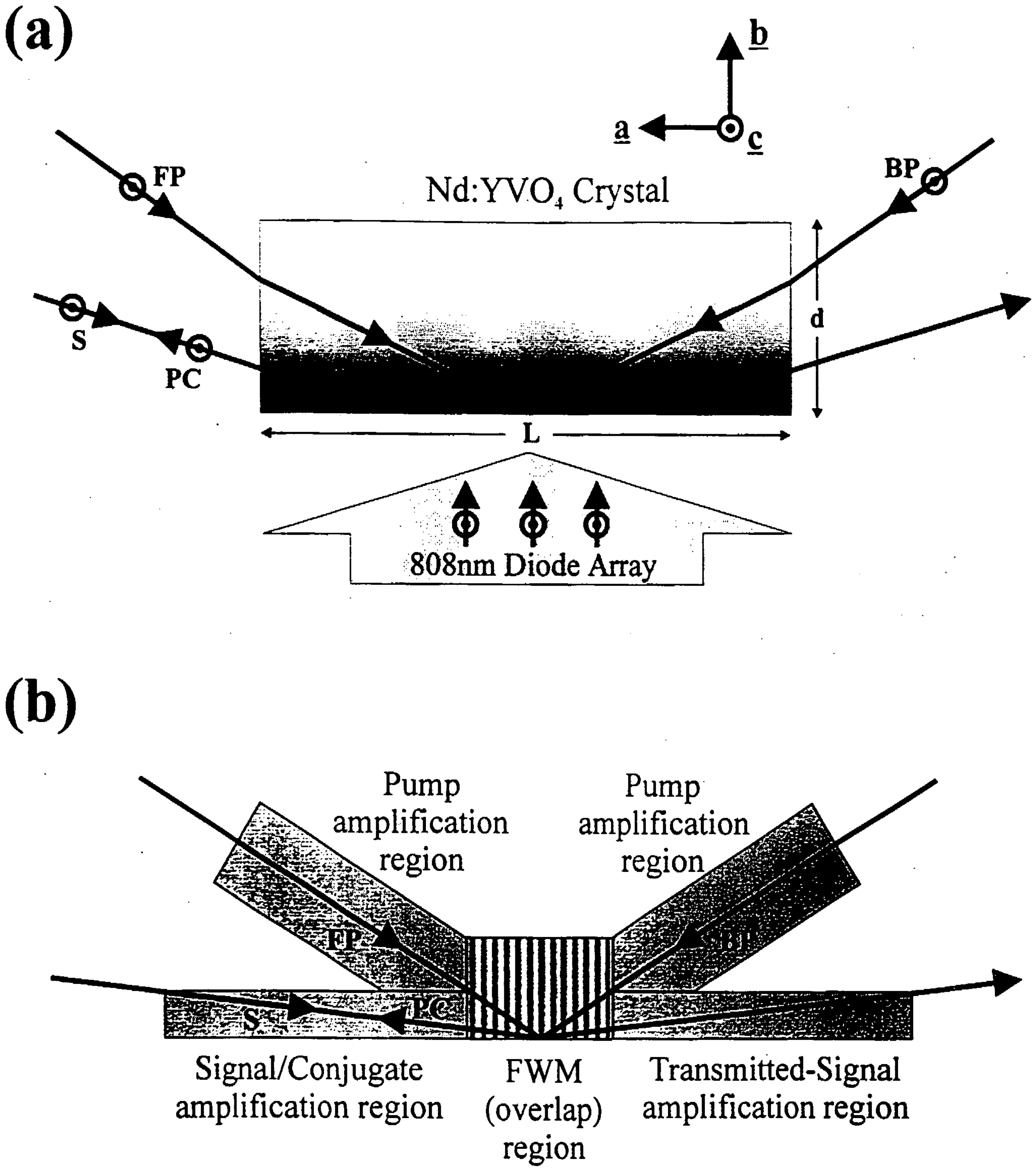
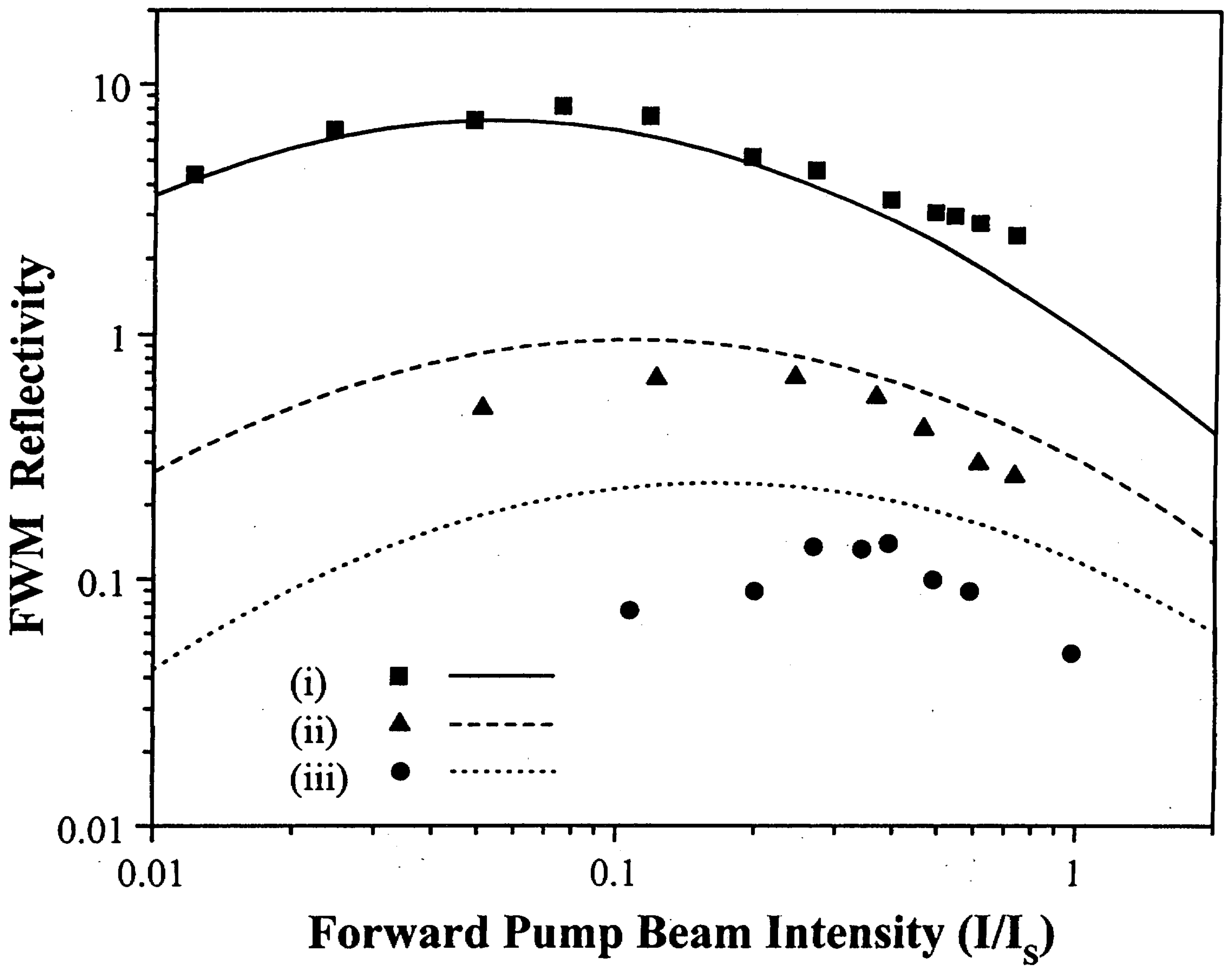

(a)
b
a
c
FP
BP
Nd:YVO$_4$ Crystal
S
PC
d
L
808nm Diode Array
(b)
Pump
amplification
region
Pump
amplification
region
FP
BP
S
PC
Signal/Conjugate
amplification region
FWM
(overlap)
region
Transmitted-Signal
amplification region

fig 3


FWM Reflectivity
10
1
0.1
0.01
0.01
0.1
1
Forward Pump Beam Intensity (I/I_s)
(i) ■
(ii) ▲
(iii) ●