A 3.5-Watt Q-switched 532 nm Nd:YAG Laser Pumped With Fiber-Coupled Diode Lasers

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ABSTRACT

A diode-pumped laser with over 11 W of continuous-wave 1064 nm, and 3.5 W of frequency-doubled average power at 50 kHz pulse repetition frequency, has been developed. A single Nd:YAG rod was pumped with the combined output of three fiber-coupled diode laser arrays. Each pump laser was capable of 10-W cw output. The fiber output of each pump lasers was first collimated and then focused with a single lens onto one end of a Nd:YAG rod. The resonator mirrors for the L-shaped cavity were selected such that thermal lensing in the laser crystal was mostly compensated. The 532 nm output beam quality factor (M2) was less than 1.5.

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To communicate from outer planets via a laser beam to the earth, electrically efficient and compact lasers with average output power and pulse repetition frequency of greater than 2 W and 50 kHz, respectively, are needed. Other important requirements are single spatial mode beam quality, output wavelength in the visible to near infrared range, short (ns level) pulse width, low pulse jitter, and simple thermal management. Fiber-coupled diode lasers facilitate removal of heat generated by high power diode pump lasers, since the diode lasers can be cooled away from the laser resonator. Alignment of the pump laser(s) with the resonator is also simplified since the fiber delivers a manageable output from a 1-cm line source, Also, there are no complications due to thermal gradients in the laser's mechanical assembly caused by the diode pump lasers, Recently, a number of continuous-wave 1-4 (cw) and pulsed 5-8 solid-state lasers pumped with cw diode lasers have been reported. Here, we report generation of greater than 11 W of cw output at 1064 nm, and greater than 3.5 W of near diffraction-limited 532 nm second harmonic at pulse repetition frequency (PRF) of 50 kHz, with higher efficiency than earlier reports,

The 809 nm pump laser power, required to achieve over 2-W of 532 nm average output at pulse repetition frequency of 50 kHz, is greater than 20 W. Depending on the solid-state laser material used, a pump power level of 30 W (the combined output of three 1O-W diodes) focused to a small diameter, can generate significant thermal-induced lensing and birefringence. 9 For example, with a pump power absorption of 24 W in the Nd:YAG crystal, 30% conversion of the pump power into heat, and pump spot size (beam radius) of 0.3 mm, a lens with focal length of approximately 10 cm is thermally induced into the crystal.[10] Currently, the three most efficient laser host crystals for diode-pumping are YAG, YLF, and YVO_4. Among these, YLF has low coefficient of thermal-induced lensing and birefringence. But, as evidenced empirically, it has low thermal fracture strength also. The YV04 crystal has a higher thermal lensing coefficients than YAG. The thermal fracture limit of YV04 lies between that of YAG and YLF. Therefore, the Nd: YAG crystal was, selected as this laser's active medium. To specify the radius of curvature of mirrors for a single-mode resonator with large mode volume, compensation of thermally-induced lens, low sensitivity to focal length fluctuations of the lens and high alignment stability, the approach proposed by Magni was followed.11 The resonator was modeled using commercially available software (Paraxia™, Genesse Software). For 27 W of pump power and a pump spot size of 0.4 ± 0.05 mm in the crystal, two different resonators were identified; a piano-concave and a convex-concave, The concave mirror in the piano-concave resonator had a radius of curvature of 100 cm. The convex-concave resonator consisted of a 12 cm radius of curvature convex mirror and a concave mirror with radius of curvature of 100 cm. The plano-concave mirror was used in this set up due to availability of the mirrors.

Fig. 1 is a schematic of the three mirror laser resonator utilized in the experiment. This resonator configuration allows confinement of the green intracavity beam to the region containing only the frequency-doubler. The three-mirror resonator has been used earlier for both end-pumped and side-pumped configurations.[12-14] The pump laser consisted of three 1O-W fiber-coupled diode laser arrays (SDL-3450-P5) with output wavelength of lasers (at 25°C) ranging from 808 nm to 811 nm. The fiber that is coupled to each of the pump lasers had a core diameter of 0.4 mm and numerical aperture (NA) of approximately 0.4. Efficient mode-matching to the laser cavity requires re-imaging of the beam into a small spot size less than 0.4 mm in diameter with low (<0.3) numerical aperture. Proper focusing is made difficult by the characteristics of this particular fiber. The output beam of each fiber-coupled diode laser was partially collimated by an 8.6 mm focal length lens combination (Newport Research, F-L20) to a total beam diameter of 1.8 cm, measured 1 cm away from the lens. Following the approach by Fan et al[1] 5, the three closely-spaced collimated beams were focused into one end of a Nd:YAG crystal with a single 2.35 cm focal length aspheric lens (Melles Griot, 01 LAG 115). The full-width at half-maximum pump-spot radius of the focused beam at the laser crystal was 0.43 mm, as measured by a laser beam profiler (Photon Inc.). Approximately 90% of all diode laser light exiting the fibers was collected and incident on the input cavity mirror. The 7 mm diameter Nd:YAG rod (Litton/Airtron, low birefringence quality), with 1 atomic 70 Nd ion concentration, was 7 mm long. Both end surfaces of the rod were anti-reflectance (AR) coated for 1064 nm. The rod was wrapped with iridium foil and was press fit into a water-cooled copper housing. The water temperature was held at 17 “C. Active cooling was found necessary for stable output generation, but it had minimal effect on the maximum achievable output. The laser crystal was placed 1 mm away from the input mirror. The input mirror (PMS Inc.) was a 100 cm radius of curvature concave mirror with AR coating at 809 nm on the entrance face, and high reflectance (HR) at 1064 nm and high transmittance (HT) coating at 809 nm on the second surface. The flat fold mirror (PMS Inc.) had a reflectance of 99.9% at 1064 nm for s polarization and transmitted 92% of the polarized 532 nm second harmonic at 45° angle of incidence. The end mirror (PMS Inc.) was also flat, with dual HR coating at 1064 nm and 532 nm. The cavity length was 10.5 cm producing a fundamental spot size of approximately 0,52 mm at the input mirror.

The Nd:YAG laser crystal and a SF-6 glass acousto-optical Q-switcher were separated by 1.5 cm and were located in one arm of the cavity . The frequency-doubling crystal was located in the other arm. The 1 cm long Q-switcher (Gooch and Housego) had AR coatings at 1064 nm wavelength on both faces and was driven at 80 MHz center frequency with 1.4 W of RF power. Frequency-doubling was achieved by a 5 mm long, type 11 KTP (KTiPO4) crystal (ITI E-O) with dual 1064 and 532 nm AR coating on both surfaces. From the theory of Boyd and Kleinman[16], for this size KTP, the optimum spot size in the crystal is approximately 0.02 mm. However, to avoid gray tracking damage in the KTP crystal[17], the frequency-doubler was not placed at the cavity beam waist, The calculated Gaussian mode spot size in the KTP crystal was approximately 0.185 mm. This clearly results in lower than optimum doubling efficiency, but as will be discussed later, the 1064 nm light was still converted to 532 nm with an efficiency of 30%. Due to modal competition, large amplitude fluctuations of the second harmonic output commonly occur in intracavity-doubled diode-pumped lasers[18]. To enhance the stability of the 532 nm output, based on the scheme proposed by Oka and Kubota[19], a 45° dual wavelength AR-coated quarter-wave plate at the fundamental wavelength was inserted between the KTP and the end mirror. A calibrated dichroic mirror and a 532 nm band-pass filter located external to the cavity separated the second harmonic signal from residual fundamental beam. The Q-switched pulses were measured with a fast photodiode detector (E-O Technologies ET-2000). Laser power at the fundamental wavelength was measured by removing the KTP doubling crystal and replacing the HR-coated end mirror with a 95% reflectance (at 1064 nm) flat output coupler mirror.

Fig. 2 illustrates the second harmonic and fundamental average output power, at 50 kHz pulse repetition frequency (PRF), as a function of the incident cw pump power. Laser threshold for cw 1064 nm and pulsed 532 nm generation were 2.1 W and 2.5 W, respectively, measured at the input mirror of the resonator. The maximum cw 1064 nm power obtained was 11.7 W when all three pump lasers operated at full rated power (10-W) each. Approximately 21.1 W, that is 78% of the total pump power was absorbed into the laser crystal. The highest 532-nm average power obtained was 3.5 W at 50 kHz PRF. Thus, the optical-to-optical conversion efficiencies were 55% and 16.6% for 1064-nm and 532-nm, respectively. Once the intracavity elements and diode lasers stabilized thermally (within approximately 10 minutes) the laser output power levels mentioned above remained stable over several hours of operation with only ±5% fluctuation of the average power. The maximum extra-cavity 532 nm output, obtained with a single-pass through the KTP crystal was 2.85 W. In this case, the 50 kHz PRF 1064 nm beam was focused to a beam diameter of 120 µm with a 5 cm focal length lens. The second harmonic average output power and laser pulse width as function of the PRF are shown in Fig. 3. To avoid damage to the resonator optics and intra-cavity elements, the Q-switcher was always operated at above 10 kHz. The wall plug efficiency for this laser, considering all power supplied to pump diode lasers, the Q-switcher, and those for heat removal from diode lasers and laser crystal, was 2.3%.

At 50 kHz PRF, the measured pulse-to-pulse energy instability for the 1064 nm output was 4.1%, At 75 kHz PRF, the pulse-to-pulse instability was greater than 23% due to reduced gain. The same factor results in sharp increase of pulse width (to 52 ns) at pulse repetition frequencies above 60 kHz.

A measure of laser output beam quality (M2 factor) is the ratio of the far-field beam diameter to the diffraction limited beam diameter calculated for the same cavity waist[20]. Beam-diameter measurements were taken at the far-field of the laser, 2.5 meters from the output coupler. At full pump power, for the cw fundamental wavelength of 1064 nm, the measured beam divergence was 3.6 mrad, and the diameter of the beam waist was 0.41 mm. These values yield a beam quality factor of 2,2. The Q-switched 532 nm output beam quality was approximately 1.5 times the diffraction limit. This shows that the intracavity KTP crystal acts as a filter, preferentially doubling those intracavity beams that are of higher quality (M2 factor closer to 1). The beam quality was a function of the pump power since the focal length of the thermally induced lens, and therefore the Fresnel number for the cavity, varies with pump power.

Output characteristics of a 4 x 4 x 4 mm3 Nd:YV04 crystal, utilizing the same pump and resonator configuration, were also measured with this cavity. The initial laser output was comparable to that of Nd:YAG. However, amplitude stability was very poor, falling to zero within minutes. This is mainly attributed to thermal-induced lensing and birefringence. This resonator was designed for thermal characteristics of YAG which are very different from that of YVO4.

The laser’s overall efficiency may improve significantly by: (1) availability of more efficient diode pump lasers; (2) more efficient coupling of “diode laser output through the fiber; (3) use of two 15-W fiber-coupled lasers instead of the present three 1O-W lasers; (4) separate temperature control of each diode pump laser; and (5) use of a cavity designed around the thermal characteristics of YV04 to take advantage of its higher conversion efficiency.

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FIGURE CAPTIONS:

Fig. 1. Schematic of the experimental setup. Length of the resonator is 10.5 cm.

Fig. 2. Continuous-wave output power at 1064 nm and pulsed 532 nm output as a function of the incident pump power.

Fig. 3. **Average output power at 532** nm and laser pulse width as a function of the Q-switch pulse repetition frequency.

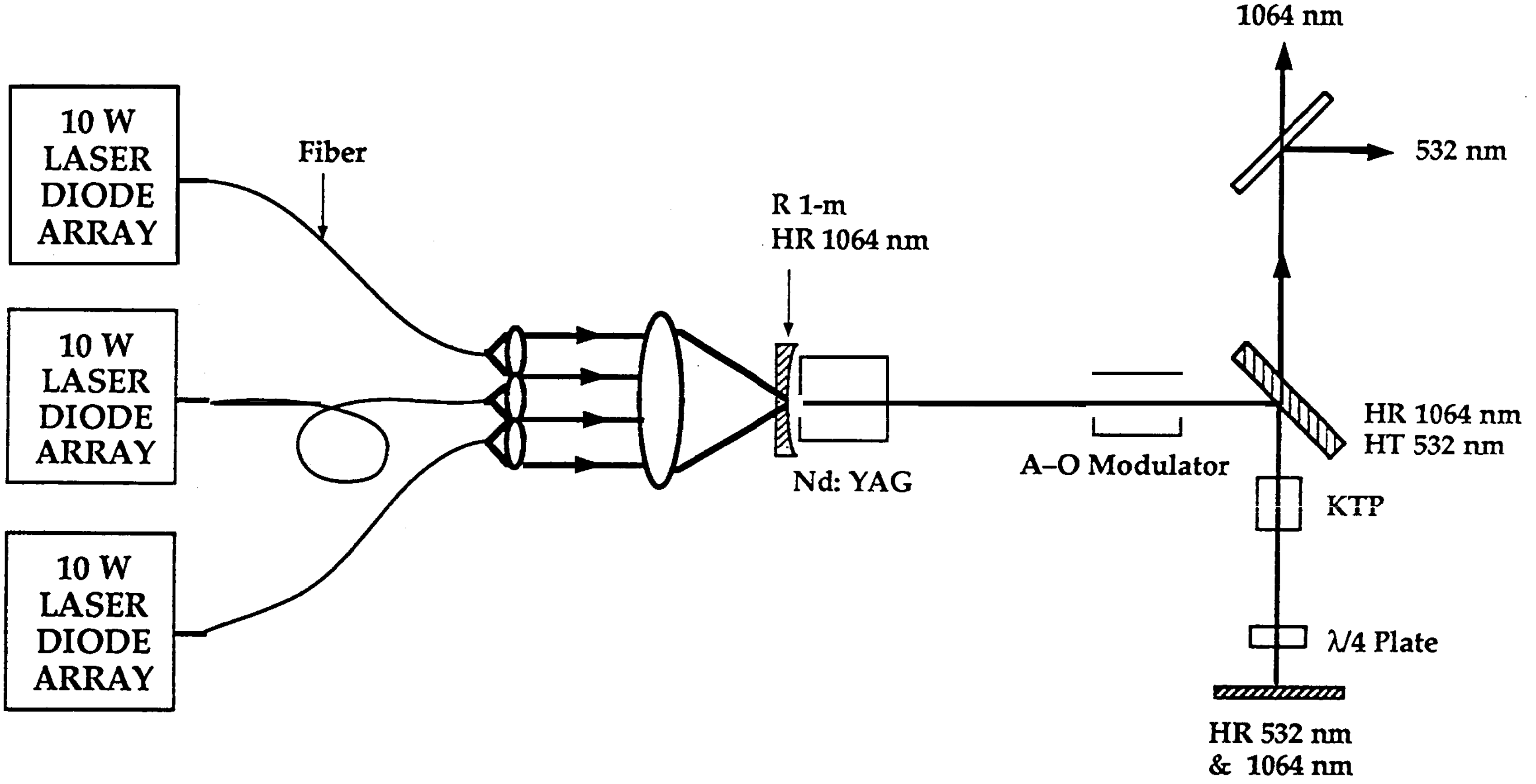
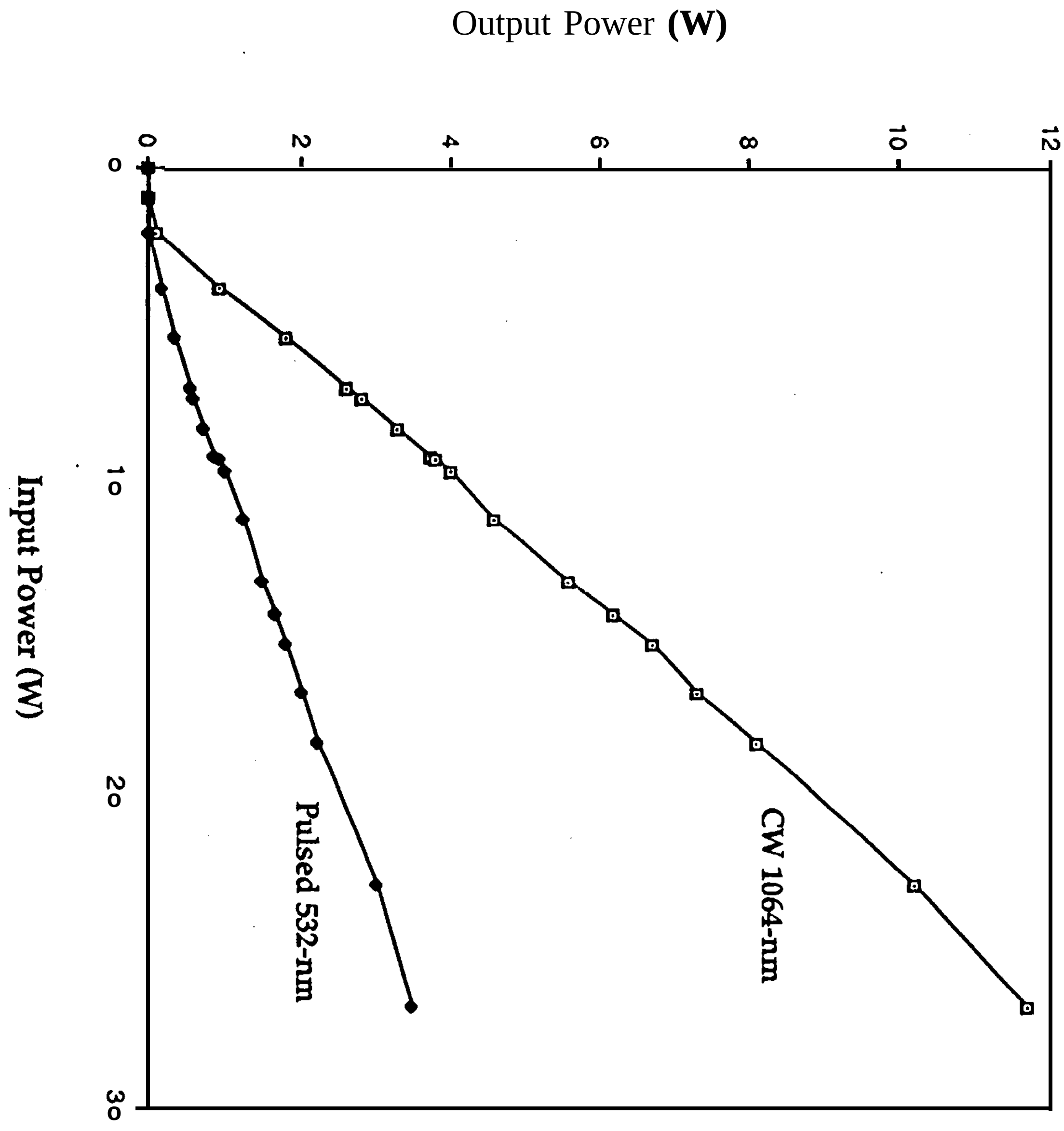

10 W
LASER
DIODE
ARRAY
10 W
LASER
DIODE
ARRAY
10 W
LASER
DIODE
ARRAY
Fiber
R 1-m
HR 1064 nm
Nd: YAG
A–O Modulator
1064 nm
532 nm
HR 1064 nm
HT 532 nm
KTP
λ/4 Plate
HR 532 nm
& 1064 nm

Fig 1


Output Power (W)
0
2
4
6
8
10
12
Input Power (W)
0
10
20
30
CW 1064-nm
Pulsed 532-nm

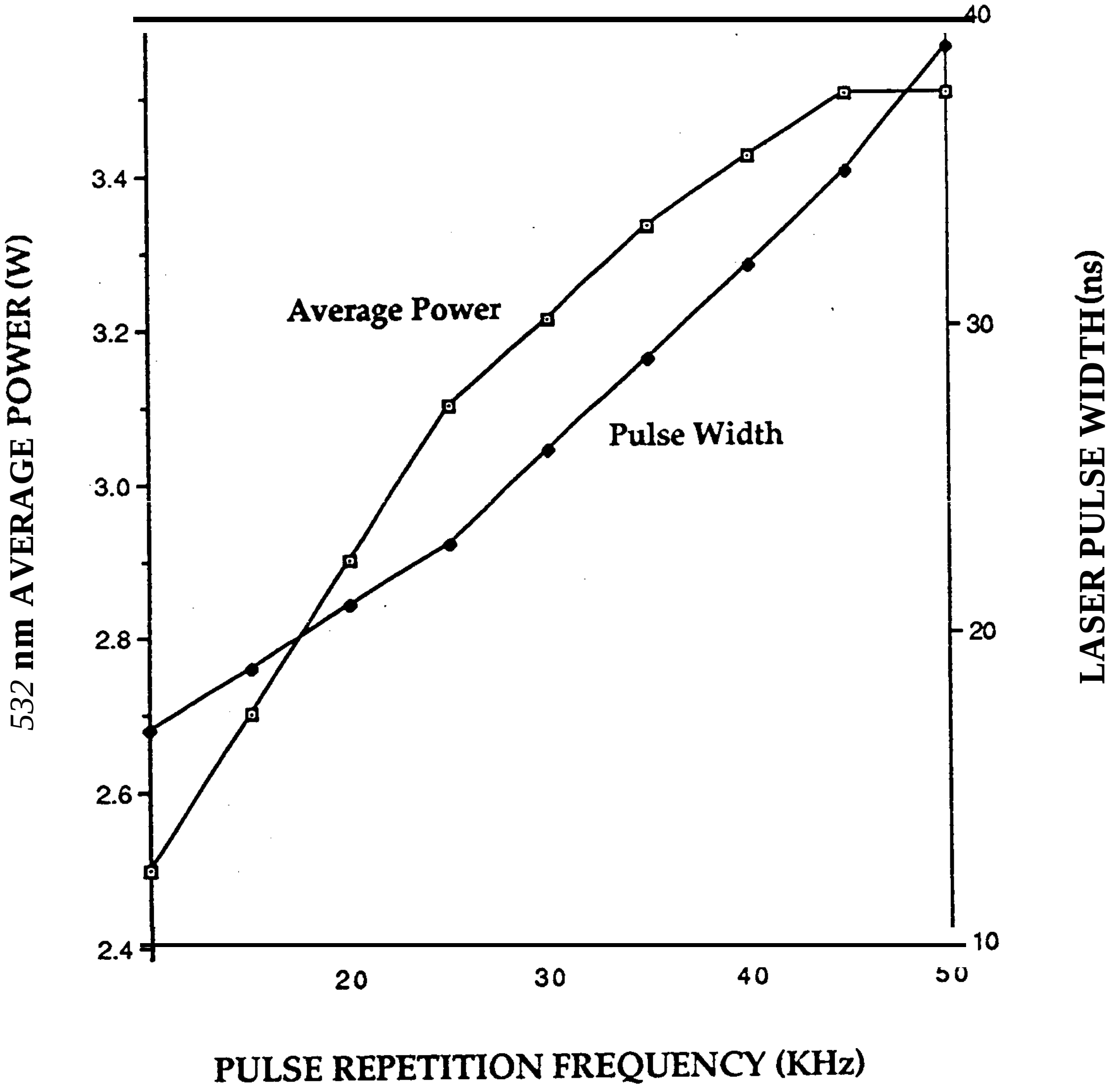

532 nm AVERAGE POWER (W)
3.4
3.2
3.0
2.8
2.6
2.4
Average Power
Pulse Width
LASER PULSE WIDTH (ns)
40
30
20
10
20
30
40
50
PULSE REPETITION FREQUENCY (KHz)

Fig 3