PRAMANA — journal of physics Vol. 75, No. 5
November 2010
pp. 883–888

Development of Raman-shifted probe laser beam for plasma diagnosis using polaro-interferometer

M P KAMATH*, A P KULKARNI, S JAIN, P K TRIPATHI, A S JOSHI, P A NAIK and P D GUPTA
Laser Plasma Division, Raja Ramanna Center for Advanced Technology, Indore 452 013, India
*Corresponding author. E-mail: kamath@rrcat.gov.in

Abstract. Optical diagnostics of laser-produced plasma requires a coherent, polarized probe beam synchronized with the pump beam. The probe beam should have energy above the background emission of plasma. Though the second harmonic probe beam satisfies most of the requirements, the plasma emission is larger at the harmonic frequencies of the pump. Hence, at high intensities we need a probe beam at non-harmonic frequencies. We have set up a Raman frequency shifted probe beam using a pressurized hydrogen cell that is pumped by the second harmonic of the Nd glass laser that operates at only one Stokes line of 673.75 nm.

Keywords. Raman-shifted probe beam; laser-produced plasma; plasma diagnosis.

PACS Nos 42.55.Ye; 42.60.By; 42.62.Eh; 42.65.Dr

1. Introduction

Self-generated magnetic fields (SMF) [1] of the order of 100 kG to few MG are generated in the high-density, high-temperature laser-produced plasmas. SMF can be estimated by measuring the Faraday rotation angle (FRA) of a linearly polarized probe laser beam passing through the plasma. The FRA is proportional to the integral of the product of plasma density and the SMF along the line of propagation of the probe beam [2]. A three-channel polaro-interferometer (TPI) [3] was set-up in Laser Plasma Division, RRCAT, India for the diagnosis of SMF in laser-produced plasma. TPI is an optical diagnostic that simultaneously measures (a) FRA of the polarization of the probe beam, (b) interferogram of the split probe beam passing through the plasma and the reference probe beam to obtain plasma density and (c) shadowgram of the plasma that gives us the record of reference probe beam used in interferometry. The probe laser beam used with the polaro-interferometer should be linearly polarized and should be of higher frequency (for probing higher plasma density than the critical density of the pump beam) and smaller pulse duration than the pump laser (to reduce the effects of integration over longer pulse duration during the measurements) and it should be synchronized to the pump beam. It should be of uniform spatial intensity distribution to avoid any artifacts in recording the interferogram and should have sufficient energy that is well above the background radiation emitted by the plasma but with low enough energy so that no significant plasma heating occur. The second harmonic probe beam satisfies most of these requirements and is generally used as the probe beam in most of the experiments at moderate intensities. The background plasma emission in the harmonics of the pump beam at high pump intensities is of higher magnitude than other frequencies because of harmonic generation in the plasma. The second harmonic beam is thus not suitable to probe high-intensity laser-plasma interactions. One solution to this problem is to use stimulated Raman (SRS) frequency-shifted probe beam in a forward scattering geometry so that it can be suitably coupled for such pump–probe experiments. One of the best Raman media (because of the large Raman frequency shift (4155 cm^{-1}) and transparency from UV to IR) is the hydrogen gas [4]. Hence, forward SRS generated from a high pressure hydrogen cell obtained by pumping it with second harmonic of the Nd:glass laser, that gives a first Stokes line at a wavelength of 673.75 nm, was used to generate off-harmonic coherent probe beam for SMF measurements. In general, the probe beam should be of single wavelength as presence of any other wavelength can have overlapping of data in the three channels of TPI. Hence, careful studies were undertaken to see that higher order Stokes and anti-Stokes lines that may be generated are removed so that the images formed in TPI are generated with the help of the first Stokes wavelength of 673.75 nm.

2. Experimental set-up

The pump laser for the plasma experiments is a two-beam Nd:glass (phosphate) laser chain that works on master oscillator-power amplifier configuration. It is sequentially optically relayed and spatially filtered. It delivers ∼100–150 GW of peak power (in a variable pulse duration of ∼0.5–1.5 ns) per beam on the target [5]. The laser chain has nine phosphate glass amplifiers (diameter varies from 10 to 80 mm) followed by a disc amplifier that amplifies a 94 mm dia. in one beam. Figure 1 shows the schematic of the probe laser beam set-up. As it is required to synchronize the SRS probe beam with the pump laser, the second harmonic pump of the SRS probe beam was generated by tapping a small energy of ∼150 mJ from the main high-power Nd:glass pump laser beam using a BK-7 glass blank wedge (with a large wedge angle of 3°) after the spatial filter R5-6 of the laser chain, as shown in figure 1. It was verified that the wedge angle was sufficient enough so that the reflected beam did not give interference fringes due to interference between the reflections between the first and second surfaces of the wedge. The polaro-interferometer is set up on a plasma chamber, at a distance of ∼21 m from the glass wedge. The distortion of the spatial profile because of diffraction during propagation over such a large distance was overcome by sequential relaying in the optical relays R-1, R-2 and R-3. The first two optical relays de-magnified the probe laser beam to a diameter of ∼13 mm from initial beam diameter of 63 mm. Low-pass spatial filtering of the laser beam below 1.5 lines/cm was also done in R-1. Table 1 shows the focal lengths of the plano-convex lenses used in the relays, the

Table 1. Design parameters of the relay systems (F_1 and F_2 are focal lengths of input and output lenses respectively).

RELAY	F_1 (m)	F_2 (m)	Magnification	Object distance (m)	Image distance (m)	Beam dia. (mm)	Total distance (m) from the Wedge to the image plane
R 1	3	1	0.33	3.75	0.92	21.0	8.67
R 2	2.5	1.5	0.6	2.57	1.47	12.6	16.71
R 3	1	1.6	1.6	1.23	1.00	20.16	21.54

object and image distance for each relay, the distance propagated by the beam from wedge W upto the image plane of that relay and the magnification/demagnification and the diameter of the beam after each relay. A variable delay line of ± 2 ns was provided to study the temporal evolution of the plasma. An Nd:glass laser amplifier with a diameter of 15 mm was used to amplify the 1054 nm beam to an energy of $\sim$1 J with a pulse duration of 1.5 ns and intensity of $\sim$190 MW/cm^2. The glass laser beam incident on the crystal was linearly polarized at 45° to the horizontal, because it passed through a Faraday isolator in the laser chain before the wedge W. A type-II KDP crystal was used to obtain the second harmonic of the pump laser beam at 1054 nm because it gives us the second harmonic beam that has suitable horizontal linear polarization direction, that is the same as the input polarizer direction of polaro-interferometer. A energy of $\sim$150 mJ could be obtained in the second harmonic at a conversion efficiency of $\sim$15%. A 1 m lens (input lens of relay R-3) focussed the second harmonic beam into hydrogen gas filled cell (pressure $\sim$20 bar) of length 56 cm. The beam was re-collimated using another lens of focal length 1.6 m (exit lens) that magnified the red SRS beam to a diameter of $\sim$20 mm. The input aperture of the polaro-interferometer is rectangular with 10 mm $\times$ 5 mm dimension. The red beam was magnified to much higher spatial size than that of the input aperture of the polaro-interferometer because it gave us flexibility to choose that part of the beam which had flat-topped spatial intensity distribution and no artifacts.

The probe beam should have higher energy than the background light emitted by the plasma. A probe beam of about 20–30 mJ energy was required to meet this requirement. Figure 2 shows the graph of conversion efficiency of the green pump beam to the first Stokes frequency obtained as a function of the input second harmonic pump energy. It was found that conversion of $\sim$25% was obtained at an input energy of $\sim$65 mJ in the second harmonic. Hence, the red probe beam of the desired energy of $\sim$20–30 mJ could be easily obtained. The polarization of this beam is the same as that of the green beam and hence is matched to the input polarization of the polaro-interferometer. The 1054 nm laser beam had a pulse duration of $\sim$1.5 ns. The second harmonic beam that was used to pump the SRS hydrogen cell had a pulse duration of $t_{\rm p} \sim 1$ ns. The pulse duration of the first Stokes line SRS beam was measured to be the same as the pump pulse which is as expected as we are in steady state of SRS amplification [6]. The SRS red beam has the same polarization as that of the pump beam and thus is suitable from the point of view of coupling the beam to polaro-interferometer.

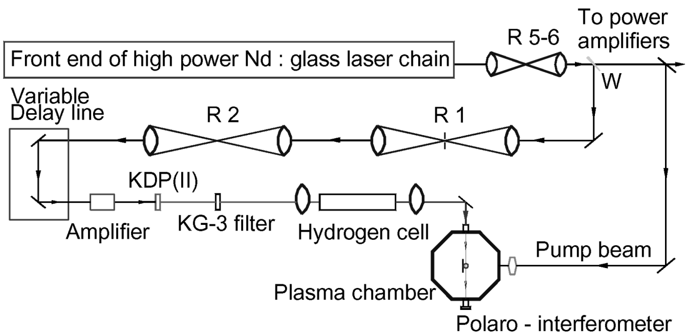

Figure 1. Schematic of the SRS probe beam.

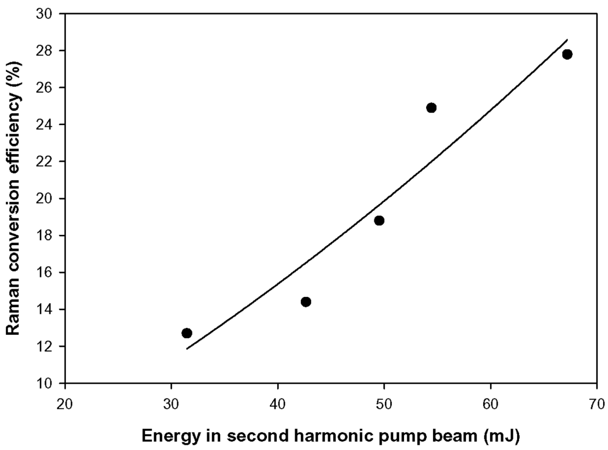

Figure 2. Conversion efficiency of hydrogen SRS cell.

It is necessary that the probe beam should be almost monochromatic so that interference, shadowgraphy and polarization rotation channels of the three-channel polaro-interferometer are recorded at one frequency and there is no other overlapped data at any other frequency. It is well known [5] that SRS from the hydrogen cell will always have higher-order Stokes/anti-Stokes frequencies generated. A colour glass filter RG-610 is put in the path of the probe beam to remove the 527 nm that is left after the SRS from the hydrogen cell. The filter thickness was chosen as 6 mm (2-, 3-mm thick filters) to give a transmission of less than 10^{-4} throughout the visible range. This filter cuts off not only 527 nm radiation to the desired levels but also the anti-Stokes frequencies in the visible region. Hence, the anti-Stokes lines in the visible region are cut off by the filter and have no contribution in the three channels of the TPI and the ones in UV will be cut off by other glass optics. The first and the second Stokes lines detected in the spectrum were recorded with Ophir wavemeter wavestar 1.05 and are shown in figure 3. The second Stokes line was weak, hence it could be observed only when the output of the first was saturated. It was observed that the ratio of the first and the second Stokes line at 673.75 nm

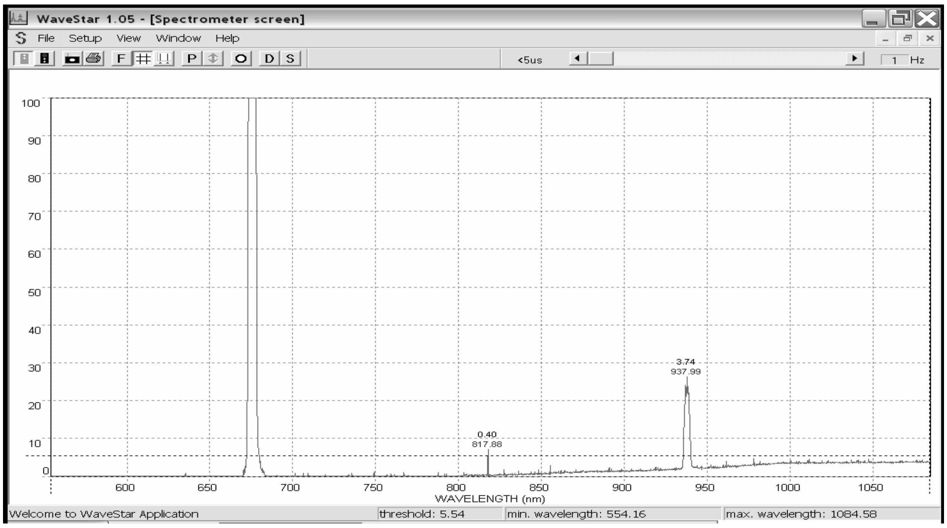

Figure 3. Stokes spectrum of hydrogen showing the first Stokes wavelength at 673.75 nm and the second at 937.99 nm.

and the 937.99 nm was between 1 : 100 and 1 : 200. Exact measurements could not be made as in one frame of the wavemeter only one of the wavelengths could be observed to full magnitude. If in some applications, even this small amount of energy in the second Stokes line is detrimental, a dispersive prism can be put in the beam line of the probe beam to avoid the unwanted contribution.

3. Conclusion

A probe laser beam operating at non-harmonic frequency of the high power laser pump beam at 1054 nm that produces the plasma was developed. The Raman-shifted SRS probe beam operating at 673.75 nm was generated by pumping a hydrogen cell by second harmonic pump beam generated from the 1054 nm high power laser beam. It gave an output that is of energy of ∼25–30 mJ, of desired linear polarization, of ∼1 ns pulse duration, synchronized to the pump beam and could operate in a single Stokes line at 673.75 nm. Such a probe beam has all the desired properties that are required for optical probing of the plasma.

Acknowledgements

The authors thank S R Patwa and J D Singh for the mechanical support in general and fabrication of high pressure hydrogen cell and M S Ansari, N Sreedhar and Ramesh Chandra for the electronics support and wiring the power supply of 15 mm diameter amplifier.

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