Focal-plane imaging of crossed beams in nonlinear optics experiments

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Abstract

An application of focal-plane imaging that can be used as a real time diagnostic of beam crossing in various optical techniques is reported. We discuss two specific versions and demonstrate the capability of maximizing system performance with an example in a combined dual-pump coherent anti-Stokes Raman scattering – interferometric Rayleigh scattering experiment (CARS-IRS). We find that this imaging diagnostic significantly reduces beam alignment time and loss of CARS-IRS signals due to inadvertent misalignments.

Keywords: focal plane imaging, crossed beam viewing

PACS: 0.690.+v, 42.60.Jf

Over the last 30 years, many optical techniques that use multiple laser beams in either collinear or crossed beam geometrical configurations have been developed. In laser Doppler velocimetry (LDV) two laser beams are focused and crossed to generate an interference fringe pattern in a small volume, where moving seed particles scatter laser light. The Doppler shift of the scattered light provides flow velocity information. To help with beam alignment before measurement, a microscope objective is positioned extremely close to the focal plane of the sample volume on an optical axis oriented in a parallel direction to the laser beam propagation. The interference fringe pattern is projected[1] with magnification onto a screen for visual inspection. Another method that uses crossed, focused laser beams is non-resonant laser-induced thermal acoustics (LITA)[2], which can be thought of as an equivalent LDV for measuring velocity without requiring seed particles. In this method two beams are crossed to produce an interference fringe pattern. Two counter-propagating sound waves generated at the measurement volume are probed with a third laser beam incident at a specified angle to the sound waves plane. The diffracted probe beam contains information to directly solve for one component of velocity, speed of sound and temperature. The direction of the scattered signal beam depends strongly on the input beam crossing.

In dual-pump coherent anti-Stokes Raman spectroscopy (CARS)[3] system, spectrally narrow green (seeded Nd:YAG at 532 nm) and yellow (554 nm) pump beams and a spectrally-broad red (607 nm) beam (used as the Stokes beam) are focused at the measurement volume using a phase matching geometry. More recently, interferometric Rayleigh scattering (IRS)[4] and simultaneous dual-pump CARS-IRS[5] have been reported using multiple 9-nsec laser pulses to increase the Rayleigh signal intensity. Although CARS is one of the more widely used methods in combustion diagnostics for gas temperature and species concentration measurement, the combined CARS-IRS technique gives a more complete measurement of the combustion environment, including velocity. In this combination, the 532 nm (green) pump beam in a standard dual-pump CARS setup is used also for Rayleigh scattering, and the Rayleigh Doppler shift is used to determine velocity. To enhance the Rayleigh signal (without gas breakdown), a pulse stretcher is used to generate at least three consecutive collinear green beams in the sample volume in a short period of time usually about 40 nsec.

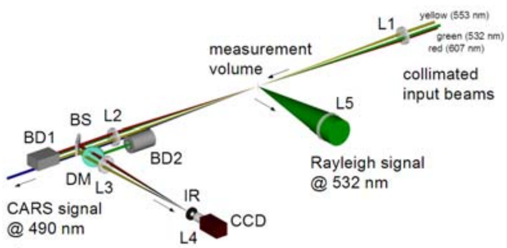

Figure 2. Optical setup for monitoring multiple laser beams in the crossing region of a simultaneous dual-pump CARS-IRS experiment.

In all of the above examples, in the past, the phase matching geometry (beam overlap) and beam focusing quality have usually been checked with photographic paper burns, knife-edge profiling, or pinhole masks before the gas measurement is performed. The multiple collinear or crossed beams (typically three) used in these nonintrusive optical arrangements must be accurately aligned at the measurement location for optimum signal generation.

In this note, we report an approach for a focal-plane imaging diagnostic that can be used to monitor and to optimize beam crossing (and implicitly signal generation) in real time in many of these nonlinear optical techniques. We describe the optical arrangement and demonstrate its capability as a monitoring tool in a combined dual-pump CARS-IRS experiment, requiring the overlap of five laser beams.

An early version for beam crossing optimization has been used in recent development of the seedless approach to fluid velocimetry with LITA[6]. A beam splitter picks off a small fraction of the input beams right after the focusing lens of the system. A microscope objective lens, placed near the focal plane of this second crossed beam set, is used to image the beam crossing on a standard CCD video camera. Neutral density filters are used to equalize the reflected intensity of all beams to the intensity range of the imaging camera. The video camera images can be used as a reference to monitor the beam crossing in the sample volume with a high degree of reliability. If the magnification is large enough, the video image can also be used to measure the spatial mode profile of each input beams. One limitation of this particular method is that it produces an independent copy of the beam crossing on the camera, relative to the true overlap in the measurement volume. Therefore, the image of the beams used for monitoring is distinctly different from that at the measurement location. However, this characteristic does not preclude the setup from being extremely useful for alignment purposes. Secondly, the energy of the input beams is reduced by the insertion of the beam splitter in the optical path. Doerk et al.[7] used a similar beam profiler/overlap system in a narrow-band BOXCARS technique.

In this work, we use a different optical design (relative to that of Refs. 6 and 7) that is shown in the schematic of Fig. 1 for a CARS-IRS technique.[5] In this arrangement, a real image of the beams at the sample region is produced on the video camera. This method does not waste input beam energy to generate this image.

To analyze the beam crossing and profiles in this optical arrangement of CARS-IRS, the three output beams (which are usually ignored in a typical CARS application) are now collected and collimated by lens L2. The beams are isolated from the outgoing CARS signal beam (blue at 490 nm) using the rectangular beam splitter BS and refocused by lens L3. Note that BS is placed above the signal beam causing no loss in signal. A dichroic mirror DM, centered at 532 nm with maximum reflectivity at 45 deg, further reduces the green beam energy (which usually is the highest). Angular tuning of the mirror around the maximum reflectivity position allows adjustment of the transmitted energy. The excess energy of the green beam reflected by the mirror DM is directed toward the beam dump BD2. Depending on the beam energy, neutral density filters (not shown) must be used in the optical path to equalize the beams intensities before reaching the camera. A microscope objective lens L4 is placed near the crossing plane of the focal region of lens L3 to image a magnified replica of the crossing beams region on the CCD camera (black and white or color). The iris IR is used to remove stray light and secondary images of the beams that are eventually formed by the beam splitter BS. As L4 and the camera are simultaneously translated parallel to the optical axis, different planes near the crossing point can be observed. Beam intensity profiles, crossing, and overlap can be conveniently observed, permitting beam adjustments in real time.

Results of this particular version on a CARS-IRS system using pulse stretching are shown in Fig.2, where a transverse plane image shows the three input CARS beams and secondary (time delayed) green beams (used to generate more Rayleigh signal) as they pass through the focal (sample) region. The contour lines of Fig. 2a show curves of constant intensity using an arbitrary intensity scale. The focal length of L1 is 400 mm, the collimated beam diameters are about 10 mm (at maximum aperture) on the lens L1, and the focused beam diameters vary approximately from 50 to 100 μm, depending on wavelength. These measured beam diameters were based on a calibration (6 μm/pixel) using a slit of known width positioned at the focal point. These measured diameters are slightly larger than those obtained with diffraction-limited Gaussian beam calculations.

Normally the beams are imaged at the exact crossing plane where they are overlapped, when adjusting the CARS-IRS apparatus. For illustration purposes in Fig. 2a, by appropriate positioning of the microscope objective L4, the green, yellow and red beams are imaged in a plane about 4 mm from the center of the measurement volume. This is about one half of the confocal parameter ($2z = 2\pi\omega^2/ \lambda$) if $\lambda = 532$ nm and minimum beam radius $\omega \sim 25$ μm. The beams are separated by about 300 μm at this location. In Fig 2a, the green spot consists of three separate and overlapped beams, used in common for both CARS (first beam) and Rayleigh (all beams) signal generation. A three-dimensional magnified image of the three overlapped 532-nm laser beams coming from the pulse stretcher and the purposely-misaligned three green beams are shown in Figs 2b and 2c, respectively. Without use of this device, we would not necessarily know that the pulse stretcher was out of alignment. Thus, Rayleigh scattering intensity from several different spatial locations would be collected, resulting in an undesirable spatial averaging of the measurement. Using this device, we can assure optimal spatial precision. The intensity beam profile in Fig. 2b shows the spatial non-uniformity produced by overlapping the secondary laser beams coming from the pulse stretcher. Good overlap of all beams at one point, obtained by extended and tedious tuning of the pulse stretcher, is almost impossible to obtain without this real time viewing system.

This version of the system was recently used to diagnose, in real time, less than optimum (yellow) pump and (red) Stokes dye beam profiles, which in turn explained why the CARS signal was significantly lower than expected. In particular, the yellow beam was found to have a crescent shape at the focus even though the beam looked round at the exit of the dye laser. Adjustment of this dye laser resulted in an improved beam shape, shown in Figure 2a. In addition to helping with beam crossing and laser alignments, this focal plane imaging technique has the capability of detecting laser beam steering. For example, we readily observed fluctuations in beam intensities and spatial locations during supersonic flow experiments due to environmental vibrations and gas refractive index fluctuations.

In conclusion, we have described an optical arrangement that allows real time observation of laser beam profiles and optimization of beam crossing by imaging the focal plane of multiple crossed laser beams onto a single video camera. It was found to be extremely useful for rapidly obtaining maximum measurable signal in LITA, CARS, and CARS-IRS techniques. This simple diagnostic tool will be extremely helpful during setup and operation of a variety of linear and non-linear optical techniques that use multiple input laser beams.

We thank R. C. Hart for initial inspiration, P. M. Danehy for helpful discussions, and the Hypersonic Airbreathing Propulsion Branch for the use of equipment and the laboratory.

References

1. W. H., Young, Jr., J. F. Meyers, D. R., Hoad,"A Laser Velocimeter Flow Survey Above a Stalled Wing," NASA TP-1266, see Fig. 2 (1978).

2. D.E., Govoni, J.A., Booze, A., Sinha, and F. F., Crim, "The non-Resonant Signal in Laser-Induced Grating Spectroscopy of Gases," Chem. Phys. Lett., **216**, 525-529 (1993).

3. R.D., Hancock, F.R., Schauer, R.P., Lucht, and R.L., Farrow, "Dual-Pump CARS Coherent Anti-Stokes Raman Scattering Measurements of Nitrogen and Oxygen in a Laminar Jet Diffusion Flame," Appl. Opt., **36**, 3217-3226 (1997).

4. D. Bivolaru, P. M. Danehy, J. W. Lee, R. L., "Intracavity Rayleigh-Mie Scattering for Multipoint, Two-Component Velocity Measurement," Opt. Lett. **31**, 1645-1647 (2006).

5. D. Bivolaru, P. M. Danehy, K. D. Grinstead, Jr., S. Tedder, and A. D. Cutler, "Simultaneous CARS and Interferometric Rayleigh Scattering," AIAA-2006-2968, 25th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, San Francisco, CA, June 5-8, 2006.

6. R. C. Hart, G. C. Herring, and R. J. Balla, "Common-Path Heterodyne Laser-Induced Thermal Acoustics for Seedless Laser Velocimetry", Opt. Lett. **27**, 710-712 (2002).

7. T. Doerk, J. Ehlbeck, P. Jauemik, J. Stanco, J. Uhlenbusch, and T. Wottka, "Diagnostics of a Microwave CO_2 laser Discharge by Means of Narrow-Band BOXCARS," J. Phys.D., Appl. Phys. **26**, 1015-1022, 1993.

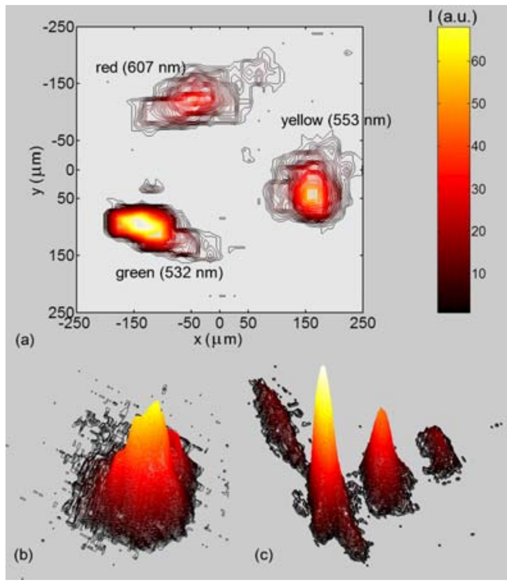

Figure 2. Laser beam profiles of simultaneous, single-point, dual-pump CARS-IRS: (a) the spatial location of the three input CARS beams in a plane transverse to the common beam direction located about 0.5 confocal parameter from the exact focal plane, (b) a magnified view of the transverse profile of the 532-nm pump beam which consists of three overlapped and collinear pulses from a pulse stretcher, and (c) the same three 532-nm beams when they are purposely misaligned for illustration purposes.

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