Radiation monitoring of lasers with variable output

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ABSTRACT

The transition from the conventional concept of “laser in the lab” to that of “lab in the laser”, which implies the presence in a laser with variable output parameters of all the necessary built-in sensors for characterisation of the output radiation, is prompted by development of a new generation of devices and/or techniques enabling this function. The potential of speckle-based technologies is discussed in this respect, including the use of special surfaces. It is shown that the recent progress in image acquisition imparts to the speckle-based technologies a new potential both for universal monitoring of radiation parameters and for AI-assisted control.

Keywords: speckle-based technologies, lab in the laser, AI-assisted control

1. INTRODUCTION

Output radiation parameters in many lasers and laser systems require live characterisation because such major parameters as radiation wavelength, spectral width, spectral and amplitude instability (in case of continuous-wave radiation), pulse shape and duration (in case of pulsed operation) may fluctuate during operation or from one session to another. This naturally does not apply to those lasers whose radiation parameters are not adjustable (such as laser pointers) or where the only substantially adjustable parameter is the output power (e.g. DPSS pumping lasers and others). There exists a broad category of lasers (tuneable solid-state, dye-jet, and so forth) whose main output parameters may be adjustable or tuneable. These lasers are commonly used within the concept “laser in the lab”, which means that for measurement of the key parameters of the output radiation, highly specialised equipment is necessary (such as wavelength meters, etc.) that is often more complicated and expensive than the laser system itself. It should be pointed out that the need of such special equipment significantly impedes broader application of lasers with variable output parameters. Consequently, a question arises as to the possibility of radiation parameter measurement by “internal” means or with the help of simple and inexpensive accessories that could be either included into the laser kit or offered as a basic add-on. Conceptually, this may be termed a “lab in the laser”, which would make self-sufficient lasers with adjustable parameters as far as measurement of those parameters is concerned.

It may be possible to implement this new “lab in the laser” conception on the basis of speckle interferometry[1], which uses the effect inherent in almost any laser radiation. Typical speckle patterns emerge when laser beams experience interference interacting with a surface (reflective or transparent) with a random profile[2]. Interferometric nature of these patterns makes this approach quite sensitive, this is why it was earlier used for precise measurement of surface profiles[3–6]. By turning this approach around and making the surface profile fixed (optimisation of this profile is a research problem in its own right), it is possible to characterise the properties of radiation instead. A speckle image encodes information about the major parameters of the laser radiation producing it, and the “only” problem is how to extract the needed information from this image with sufficient precision. There is a growing hope for successful resolution of this problem fuelled by emerging demonstrations of relatively precise measurement of radiation wavelength from speckle images[7–11]. Technically, this may be a small device (a black box, essentially) with a means of connection to a computer (such as USB or wireless connectivity). Laser radiation is guided into this box through a fibre waveguide and inside, it strikes a specially profiled reflective surface positioned in a desired way relative to the waveguide exit. Capture of speckle images with sufficient resolution may be carried out with a camera similar to those used in modern consumer-grade mobile devices.

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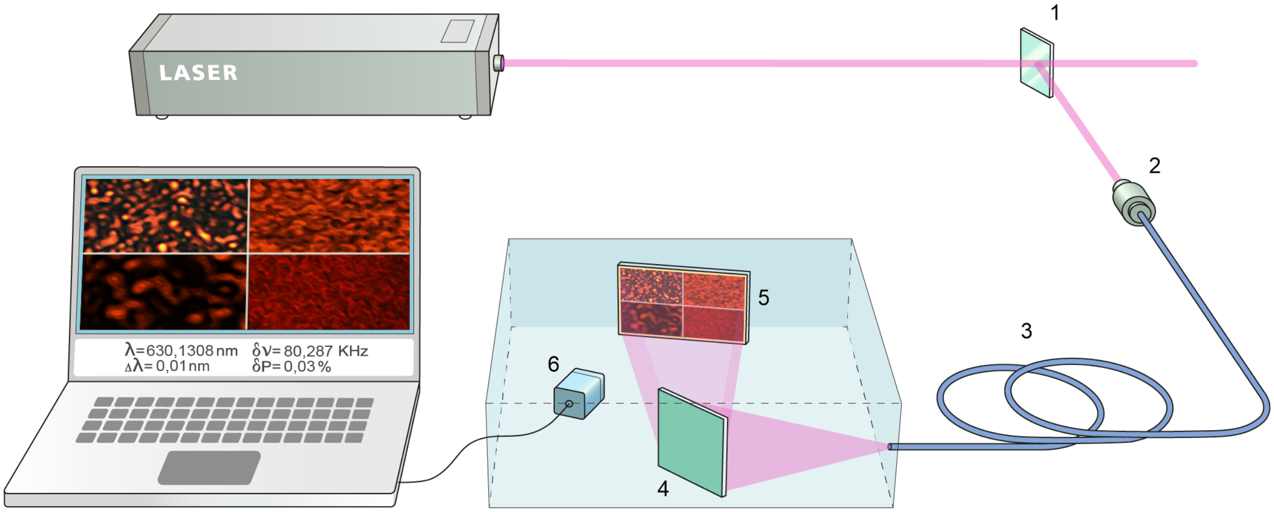

Fig. 1. Characterisation of laser radiation by speckle interferometry: 1 – beam splitter branching off a small fraction of the output, 2 – collimator for guiding the radiation into the optical fibre, 3 – optical fibre, 4 – diffusive surface forming speckle patterns, 5 – screen, 6 – camera.

2. CONCEPT

Application of speckle interferometry for measurement purposes is practical thanks to several reasons. First of all, the speckle effect occurs naturally in lasers because of laser radiation coherence[12]. Hence, for manifestation of this effect, one only needs a diffusively reflective (or transparent) surface. This means that in the presence of laser radiation, relatively small expenditures are required to observe speckle patterns. Secondly, as it was already mentioned earlier, speckle images are formed due to interference of coherent laser radiation reflected from (or passing through) a surface with random profile. It is necessary to emphasise the high (phase) sensitivity of the interference process and its similarity with physical effects used in many measurement devices (radiation wavelength meters, autocorrelators, etc.). Essentially, a speckle interferogram encodes all the desired information about the key parameters of the studied radiation (wavelength, spectral width, and so forth), but the specific relation between these parameters and the interferogram shape is not obvious. This relation may be established with the help of machine learning methods, which has already been successfully demonstrated on the example of radiation wavelength measurement. To simplify the problem and improve the measurement accuracy, the reflective (or transparent) surface may have a specific known profile. Furthermore, this surface may be segmented in order to provide different spatial scales of interference (analogous to interferometers with different base length). Such surface (a small plate) may be shipped together with a laser source of radiation and used for speckle pattern 'deciphering'. Capture of speckle images and their treatment may be carried out with the camera of an average smart phone and a portable computer.

Such a measurement device may be simple as schematically shown in Fig. 1. Depending on the output power of the laser system, a fraction of its radiation may be deflected toward this device with a fiber either from the output beam or from the surface of some intra-cavity element. Employment of single-mode fiber allows to fix the optimal angle of radiation incidence on the special surface and the distance from the fiber output. Stability of the conditions under which speckle images are recorded in combination with a known diffusively reflective (or transparent) surface will enable efficient application of machine learning methods on large sets of speckle patterns with the aim of extracting spectral and stability parameters of the studied radiation.

The detection system may be also simplified by recording the speckle pattern directly on the photosensitive matrix (without a separate surface or with the diffusive element mounted directly upon the photosensitive sensor). In this case, the measurement device may be more compact and designed as a small attachment to the laser.

The advantages of this approach to measurement of laser radiation parameters consists in the absence of need to use bulky, expensive, and complex measurement apparatus for determination of the same radiation parameters. Besides, this need of measurement equipment puts a limit to the application area of many laser devices, essentially rendering their fully efficient operation only possible in laboratory conditions. Many lasers fall into the concept of “laser in the lab” namely because their operation implies the need of additional measurement equipment (wavelength meter, interferometer, and so forth). Implementation of built-in characterisation of radiation parameters will enable transition toward the novel concept of “lab in the laser” and lead to substantial growth of the application sphere of universal laser systems, allowing their use in diverse environments outside the laboratory.

3. DISCUSSION

For a long time, speckle interferometry was mostly considered a method of surface parameter characterisation, in which radiation reflected from (or passing through) the examined surface forms speckle patterns. The radiation parameters in this approach were hitherto taken as known. Properties of laser speckle images were actively used for measurement of parameters of static[13–15] and dynamic[16–18] processes in relation to reflective or transparent surfaces. There is even a special term “biospeckle”, which was coined in bio-medical optics applications for images generated by biological object surfaces. The main difficulty in speckle pattern analysis arises due to the unknown profile of the reflective (or transparent) surface. In this problem, the unknown and known parameters may be swapped, that is the surface profile taken as known (a specially fabricated surface), whereas the radiation parameters as sought for. Finding the spectral parameters of laser radiation by processing special speckle images is not impossible, the only question is in the achievable accuracy. Recent studies have shown[19] that the accuracy of radiation wavelength measurement may be at least as high as 10^{-6} when a single-mode optical fibre is used for speckle image formation. This demonstrated solution has a drawback of relatively narrow working spectral range (only 80 nm), but introduction of specially fabricated surfaces for speckle pattern generation will substantially broaden this range and improve measurement precision.

This method of measurement of radiation spectral and stability parameters has a number of clear advantages. First of all, such a system may be implemented as a compact and inexpensive laser accessory and replace the conventional laboratory measurement complex. Secondly, this approach to radiation parameter measurement, in which key parameter monitoring does not require laboratory environment, allows significantly larger application area of lasers with adjustable radiation parameters. Third, operation of such lasers becomes easier due to the built-in possibility of live measurement of their main parameters.

4. FEATURES

The working spectral range of the method is limited through two major factors: the reflectance (or transmittance) of the surface (medium) that forms the speckle pattern and the working range of the imaging device that registers the pattern. Hence, this working range may be quite broad and exceed the spectral domain of a typical radiation wavelength meter. Registration of speckle patterns may be carried out in two modes. The measurement system may receive the totality of the laser output, in which case characterisation of laser radiation is done during idle time between the periods when laser output is required for the user activities. Alternatively, only a (small) fraction of the output radiation may be guided into the measurement system. In the latter case, characterisation of the laser radiation parameters may be performed simultaneously with other user activities. For this, either a fraction of the output beam may be split off into the measurement system or a naturally occurring reflection from some optical surface inside the laser cavity may be used for this purpose.

5. CONCLUSION

Utilisation of speckle patterns, which have for a long time been considered rather a deleterious phenomenon, as the basis of a measurement system will open up new application areas for many lasers with adjustable output parameters (including other than just the output power). A relatively simple and portable system for measurement of the main parameters of laser radiation will allow operation of some sources outside the laboratory environment. Perhaps, in the foreseeable future, measurement devices of this kind will become the basic means for characterisation of the key parameters of laser radiation.

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