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Sensors for photonic devices

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Abstract
This work analyses the current state of affairs related to built-in monitoring of laser radiation parameters. Attention is drawn to dearth of sensors that could measure spectral and temporal parameters of radiation at the sufficient level. A conclusion is drawn about importance of research and development and about the general progress in this field. New materials, novel technologies, and new ideas are able to facilitate development of new approaches to transformation of optical radiation parameters into electric signals and to extraction from those signals of higher-level information, to advance wireless operation and implementation of new integrated smart sensors, which are in great need.

Keywords Optoelectronic and photonic sensors · Optical devices · Lasers · Radiation monitoring

1 Introduction

Sensors are increasingly entering our life not only as fault detectors, but also as key elements for monitoring of various systems, including photonic systems. The basic principle of a conventional sensor is generation of an electric signal in response to some physical action (either mechanic or by electric field, light, ambient conditions, and so forth). Among sensors, growing popularity is enjoyed by those whose operation is not sensitive to external electric fields (electric disturbances, etc.) and that are based on interaction of reference light with the environment through optical fibre. Insensitivity of the 'sensitive' part of such sensors to external electromagnetic noise classifies them among the next-generation sensors. However, the advantages of such sensors come along with drawbacks, some significant and arising not only as the industry's growing pains, but as inherent in the detection technology itself. Therefore, classification of these sensors as advanced or belonging to the next generation may be premature. For the moment, they may be considered simply as new sensors using laser radiation within optical fibre for registration of changes in the external environment surrounding the fibre. The field of sensor research and development is becoming more and more important in relation to advances in computer technologies

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[automation, machine learning (ML) methods etc.]. The ‘eyes’ and other ‘sense organs’ of computer technologies are predominantly sensors, and here we will discuss their problems and development vectors in photonics.

Machine learning (ML) methods (Burkov 2020; Alpaydin 2020) increasingly often intrude into our life with an attempt to make it more convenient, more automated, more controlled by artificial intelligence (AI) (Russell and Norvig 2020). Many problems await solution along this path, an important one among them being the need to determine the state of the system (the required action on it depends on this state), to have objective and high-quality information about it. For this, sensors (detectors, pickup units/devices, meters) are needed that produce a signal (ideally, electric) in response to the measured physical variables. It is equally important to emphasis that as opposed to external sensors (such as gas sensors (Mandelis and Christofides 1993; Richter et al. 2000; Moser et al. 2017; Constantinoiu and Viespe 2020) used in environmental monitoring or strain sensors (Chow et al. 2005; Chen et al. 2020; Zhao et al. 2021) for structural monitoring), these should be internal ones for measurement of the system’s internal or output parameters. For a photonic system, such as free-space laser, one needs inexpensive compact sensors able to measure at the minimum the laser radiation parameters and ideally, the generation regime properties. More wide-spread introduction of ML methods is hampered, among other problems, by the lack of sensors for integral monitoring of technological systems. A laser equipped with a dozen or more of cheap and small sensors appears to-day more like an improbable ‘smart’ laser of remote future rather than as an accessible reality.

What kind of sensors are needed to turn far prospects into imminent reality? Which sensors for photonic devices should become a priority for researchers and engineers? It must be noted that research and development efforts are first of all aimed at introduction of sensor types that happen to be in high demand, for example, for food quality monitoring or for detection of harmful substances in various media. Sensors for technological devices (for measurement and selection of their state, etc.) will always remain a secondary niche market. Therefore, this field of research possibly needs special support. This work is focused on analysis of both existing sensors and those that should be yet developed for measurement of laser parameters. Physical effects that could become the foundation of such compact sensors are considered, as well.

2 Discussion

What is necessary to measure in a laser device? The most important parameter is the output radiation power, both in continuous-wave (CW) lasers and in pulsed ones (in the latter case, this may be either the average output power or the peak power in a pulse). This parameter is easily measured by splitting a small fraction of the output radiation into a photodetector (Mihailovic et al. 2004; Pinot and Silvestri 2017; Khramov et al. 2019) (this role may be played by a photodiode, for instance). A second simple sensor may be used to monitor the temperature of the laser system elements [e. g. a thermistor (Gonzalez-Reyna et al. 2015; Hao et al. 2015; Silipigni et al. 2020)]. One may also mention humidity sensors (Zhang et al. 2017, 2020a; Kim et al. 2020; Owji et al. 2021). In practice, the list of available inexpensive compact sensors for monitoring the internal state of a laser is limited by these three. Beyond it, there are complicated and much bulkier laboratory devices, which are definitely necessary, but can be classified as neither compact nor inexpensive. They will have to be transformed into such in the future.

It should be pointed out that the problem of sensors for measurement of internal parameters of photonic devices appears poorly addressed and largely neglected. The currently researched and developed sensors are aimed, quite naturally, at more popular external measurements. Characterisation of radiation sources is beyond the domain of high-priority problems, this is why many required sensors are absent or only exist as laboratory equipment. It is also necessary to note that by no means all the available sensors are small (e. g. comparable in volume to a match-head) and easily integrable into any device. Certain 'sensors' are larger and more complicated than the device itself, in which they could be used. Moreover, some sensors are, essentially, single-use (both chemical and other types). Such exotic 'sensors' will not be discussed in this work. It is here assumed that a sensor should be a miniature multiple-use device (Fig. 1) fit for integration into another, more complicated and larger system. We should also mention popularity of fibre-optical technologies in sensor fabrication (Giallorenzi et al. 1982; Kersey 1996; Kersey et al. 1997; Grattan and Sun 2000; Lee 2003; Chen et al. 2011; Fang et al. 2012; Grattan and Meggitt 2013; Rajan 2020). At a minimum, this is due to the following two primary reasons: (1) optical fibre is convenient from the viewpoint of optical technologies, since the radiation is contained within the fibre and not affected by external electromagnetic perturbations; (2) such sensors are easily integrated into fibre-optical systems that enjoy growing popularity owing to advantages in operation.

An important parameter that should be monitored in many lasers is their output wavelength. This is particularly vital for tuneable lasers, in which the output radiation

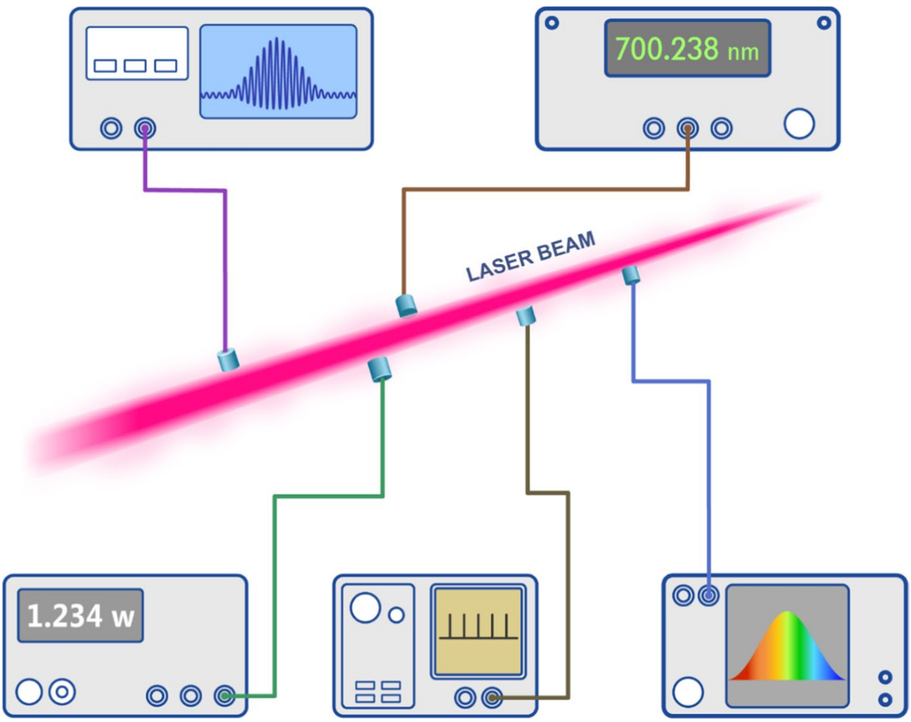

Fig. 1 Characterization of laser radiation with help weak contact or contactless sensors

wavelength may be adjusted. This parameter must be controlled as being one of the principal and variable radiation properties. In CW lasers, the required accuracy of radiation wavelength measurement may vary from several angstrom (when the output line is relatively broad and the laser operates in a multi-frequency regime) down to a few hundredths or even thousandths of angstrom (when the output line is narrow in a single-frequency regime). In pulsed lasers, the necessary accuracy may range from several nanometres (relatively long pulses with narrow radiation spectrum) to tens of nanometres (relatively short pulses with broad radiation spectrum). The principle of operation of most devices measuring radiation wavelength (wavelength meters, spectrometers, spectrographs, etc.) is based either on wavelength dependence of the angle of reflection from a diffraction grating illuminated by optical radiation (Kong et al. 2001; Solomakha and Toropov 1977) or on spectral selectivity of Fizeau wedge interferometers (Solomakha and Toropov 1977; Snyder 1978; Morris et al. 1984). Spatial dispersion may also be introduced with a prism. In the end, mechanically static measurement devices dominated their counterparts relying on mechanical movement (Ishikawa et al. 1986). The operation principle and spectral resolution directly affect the spectral measurement device dimensions. At present, there are no sensors with spectral resolution of 10^{-5} to 10^{-8}, even though research is going on in the direction of smaller and simpler devices with high resolving power (García-Márquez et al. 2003; Ouedraogo et al. 2011; White and Scholten 2012; Jones et al. 2015; Xiang et al. 2016; Duchemin et al. 2017; Dobosz and Kożuchowski 2017; Hanson et al. 2018; Hornig et al. 2019; Wang et al. 2019, 2020; Han et al. 2019; Cai et al. 2019; Bruce et al. 2019, 1929; Gupta et al. 2020; Wan et al. 2020).

Of course, in a discussion of next-generation sensors, one cannot help asking general questions. Will such next-generation sensors find their market niche? Is it even possible to create the needed sensors? The present work is premised upon positive answers to such questions. What remains is ‘only’ to invent and implement the required sensors.

Another important laser parameter is output pulse duration. For its measurement up to a certain limit, a photo-detector with an oscilloscope would be adequate. However, in order to measure ultra-short pulses (picosecond, femtosecond) the temporal resolution of relatively simple devices is insufficient. In such cases, special equipment is used, autocorrelators, streak cameras, FROG (IQFROG) techniques, etc. (Bradley and New 1974; Fork and Beisser 1978; Bradley et al. 1971; Braun et al. 1995; Hirayama and Sheik-Bahae 2002; Power et al. 2006; Walmsley and Dorrer 2009; Schubert et al. 2011; Trebino 2012; Trebino et al. 2018).

The problem of simple and compact means for pulse characterisation (duration, structure, chirp, waveform, etc.),—especially concerning relatively short pulses,—also presents a challenge to research and development community. In recent years, new approaches to this problem were proposed (Nguyen et al. 2018; Zapata-Farfan et al. 2019; Trebino et al. 2020), and it is obvious that measurement of ultra-short pulses with complicated and expensive laboratory equipment is gradually becoming a thing of the past. This is more and more addressed by considerably cheaper and compact sensors able to take the same measurements at least as fast and as accurately. Today, this field (characterisation of ultra-short and longer optical pulses) appears a promising testing ground for exploration of new approaches, new ideas with application of new materials and new physical effects.

The sensor’s ability to measure several parameters naturally makes it more valuable and allows reduction of the sensor count for characterisation of complex technical systems. It is not easy to predict the optimal number of such sensors,—3, or 13, or any other number. But it is quite clear that research in the field of multi-parameter sensors is very promising. Another interesting domain is that of ultra-compact sensors: on-chip or chip-scale.

Remotely accessible sensors are also gaining popularity, so called ‘smart’ sensors or next-generation sensors able to operate in networked swarms (Fu et al. 2019; Valeske et al. 2020; Du and Nan 2021; Sinha and Makkar 2021; Blokdyk 2018).

It is important to emphasise that the necessary parameters should be directly measured and not calculated or modelled from other measured values (Tong et al. 1997; Liu and Cui 2015; Imasaka et al. 2016). For instance, a typical mistake is indiscriminate calculation of pulse duration from its spectral width. This approach may be used sometimes (Kues et al. 2017), but in general, the relation between the radiation spectrum and pulse duration is affected by the pulse chirp, its shape, and structure. Measurement of output pulse duration and shape (structure) is a required procedure since many lasers exhibit broad variability of pulse parameters (Smirnov et al. 2012, 2017; Wollin et al. 2017; Li et al. 2018; Zhang et al. 2020b). Furthermore, this property may be introduced by the radiation delivery system rather than belong to the laser itself, i.e. it may come from external conditions.

The next type of sensors that we need is those that measure the radiation line width. It is a variable parameter in many lasers and is affected by a number of factors including the set of spectral selectors, their spectral transmittance, generation regime, etc. In pulsed lasers, the radiation line width depends upon the properties of the generated pulses, whereas in continuous-wave lasers it may depend on whether or not the laser operates in a single-frequency regime. Measurement of the radiation spectrum with a sensor presents a formidable problem, no matter whether the laser is pulsed or CW. The difference consists predominantly in that for spectral measurements of pulsed (and especially, short-pulsed) radiation, lower spectral resolution is required, whereas for CW radiation, as a rule, must rely upon interference technologies and higher spectral resolution. Implementation or real-scale radiation spectrum measurements with sensors is inherently close to that of radiation wavelength measurement. So far, both these problems are solved through use of special laboratory or commercial equipment, even though efforts are under way, which give hope that such measurement will eventually pass into the sensor domain (Xu et al. 2015; Wang et al. 2017, 2021a; Affendy et al. 2020; Lotfi et al. 2021).

Naturally, we only listed here the key radiation parameters that need measurement. Remaining outside our scope are such parameters as angular radiation pattern, its stability, etc. In any case, it is highly desirable to measure at least those key parameters with inexpensive built-in means.

What kind of general problems may be encountered in transition from the “laser in the lab” concept to the “lab in the laser” concept? Availability of necessary measurement equipment does not encourage purchase of laser systems with self-measurement of the key output parameters. Such measurement equipment available in the laboratory environment has a long life time and may be normally used with different laser systems. However, laser systems are used not only in the laboratory, and in those applications the built-in characterisation of the laser system output parameters becomes quite important. The second question is whether or not there are many such applications.

Is the development of new sensors justified, taking these applications into consideration? The answer to this last question is likely positive: this is, indeed, justified. Universal laser systems enjoy numerous applications not limited to terrestrial sphere (including lab conditions without the necessary external measurement equipment), but also in outer space. In this situation, new compact and inexpensive “internal” sensors for measurement of main radiation parameters could be of great value as part of universal laser systems. Furthermore, they may become the basis of next-generation measurement systems featuring smaller dimensions and lower cost. More compact dimensions and lower cost usually come from development of more advanced systems and transition to such smaller and/or cheaper solutions appears as one of promising vectors of development in the field of measurement systems.

Development of new sensors rests on physical effects and the contemporary level of technological capabilities, including those of artificial intelligence. Machine learning is already successfully used for solving many problems in photonics, and its domain may be extended into sensor systems, especially where large data streams are generated (for example, image acquisition, etc.).

Speckle patterns (Stetson 1987; Mandrosov 2004; Kaufmann 2011; Goodman 2020) may become one of the highly promising solutions for characterisation of laser radiation. Such patterns may be formed both outside the laser and directly in it by using a small part of reflected or out-coupled radiation. Application of speckle patterns (Archbold et al. 1978; McLaughlin 1979; Yamaguchi 1981; Kitagawa and Hayashi 1985; Rose et al. 1998; Janiczek et al. 2003; Stoller et al. 2014; Charrett et al. 2018) is appealing for several reasons. First of all, such images are a source of big data, which may be fed to algorithms of machine learning (Genty et al. 2021; Pu et al. 2020; Amil et al. 2019) in order to simplify control over certain parameters of laser radiation by the aid of artificial intelligence. Secondly, the potential held by speckle patterns in relation to measurement of radiation parameters is clearly far from being fully explored, even though many publications are appearing that study characterisation of laser radiation parameters by their means (Wang et al. 2020; Schmid and Stephan 1984; Freude et al. 1986; Redding et al. 2014; Chakrabarti et al. 2015; Metzger et al. 2017; Hu et al. 2020; Zhang 2020; Xiong et al. 2020; Zhang et al. 2020c; Wan et al. 2021a, b; Facchin et al. 2021). It is important that this technology is relatively inexpensive, and the cost of imaging equipment for speckle pattern registration tends to decline. Moreover, in certain cases, imaging cameras may be replaced by linear photo-sensors or even quadrant photo-detectors (Wang et al. 2021b). It is equally worth noting this method's universality: diverse radiation parameters,—wavelength, spectral width, power, and so forth,—may be measured by application of a single contactless sensor technology.

It should be noted that speckle patterns are often used when it is necessary to measure the properties of the surface (roughness, displacement, speed of motion, etc.) upon which the laser beam is scattered. However, the focus of the problem may be shifted onto the laser beam itself for measurement of its radiation parameters (wavelength, line width, power stability, and so forth) and, correspondingly, instead of an arbitrary scattering surface, a specially fabricated one may be used that will facilitate extraction of all necessary information from the observed speckle patterns. Specially configured reflective (or transmissive) surfaces may augment the measurement technology with new, hitherto untapped, possibilities. Speckle-based sensor technology stands to give a new impetus to the development of the methods of control and measurement of laser radiation parameters.

3 Conclusion

As a result of continuous advances in photonic devices, it becomes more and more often insufficient to have only one controllable radiation parameter. We are not concerned here with on/off devices, such as laser pointers and similar. We discuss more complex lasers, predominantly pulsed. Their broader introduction is limited by the fact that their output parameters must be monitored by expensive and bulky equipment. Purchase of such a laser often entails acquisition of an entire set of measurement apparatus, which is both larger and more expensive than the laser itself. The conventional "laser in a lab" technologies (when measurement of the key radiation parameters is essentially possible only in the laboratory) or "laser with a lab" ones (when a necessary set of measurement equipment is acquired with the laser) must give way to the modern "lab in the laser" technologies (when the laser is originally designed to include compact and inexpensive means of control and measurement of its output parameters). Highly precise, contactless, and cheap speckle-based sensor technology stands to become one of highly promising approaches to laser radiation characterisation.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflicts of interest.

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