Fibre-optical platform for research and applications

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ABSTRACT

This work considers the advantages and drawbacks of fibre-optical platforms as used for development of short-pulsed light sources and experimental research installations. Solutions are analysed, which enable active, dynamic, and tuneable control of light. A unique combination of conditions — medium dispersion, nonlinearity, and radiation spectral range — gives rise to new states of light, interesting both scientifically and practically. The prospects of the fibre-optical platforms for development of next-generation lasers and research equipment are discussed.

Keywords: fiber laser; fibre technologies; short-pulsed fibre-optical systems; all-fibre configurations

INTRODUCTION

Fibre technologies [1] are actively used to build fibre-optical platforms for scientific research and measurement equipment. Laboratory demonstrations of fibre-optical systems are often heralded as promising new-generation systems even though such systems are essentially no more than prototypes and will never go beyond the laboratory environment. The disparity between laboratory prototypes of fibre-optical systems and their possible commercial implementations arises from certain approaches followed at the development stage, which do not have more perfected counterparts applicable in end-user (or commercial) products. In this relation, fibre-optical platforms should be regarded not only as the basis for development of new-generation lasers and scientific devices, but also as a new type of experimental equipment used in scientific research. The advantages of this new type of experimental apparatus are well-known: absence of (or minimal) need of optical alignment, efficient heat removal due to large surface of the fibre, safety (total absence or minimal presence of exposed laser beams), compactness (owing to efficient packaging of fibre, for example by winding into coils). Another advantage of laboratory fibre-optical layouts is their long working life (years), as well as reliable operation and reproducible parameters in day-by-day operation.

Among the drawbacks of fibre-optical systems is the need of special equipment for manipulations with fibre (splicing, cleaving, tapering, end polishing, etc.). In the following, we will discuss the solutions that make fibre-optical platforms more convenient as used for scientific research, but complicate their application in commercial products.

2.1. Fibre-optical polarisation controllers

Fibre-optical polarisation controllers [2] are widely used in experimental practice as inexpensive devices for adjustment of the polarisation state of radiation propagating along a fibre that does not maintain polarisation. The principle of their operation is based on mechanical action, such as pressure and torsion of the fibre. Naturally, reproducibility of results obtained with such controllers is rather low because mechanical action on the fibre is difficult to measure and the description of the tuning procedure of these devices is most commonly given in the form: “when the polarisation controller is properly tuned, you will obtain this or that result”. Here, the “proper tuning” mostly means chaotically touching all the controller knobs until the desired or expected result is observed. Furthermore, the settings of radiation polarisation controllers exhibit drift and, since the principle of operation is mechanical, this drift is not always reversible because the optical fibre may undergo plastic deformation. Therefore, fibre-optical polarisation controllers are not reproducibly tuneable elements of fibre-optical systems, even though they are often used in experiment due to their affordability and simplicity.

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2.2. Material-based saturable absorbers

The greatest fault of the material-based saturable absorbers is their limited life time. It may be significant (such as 3,000–5,000 hours for semiconductor saturable absorbers [3]), but it is still limited and usually much inferior to that of other elements in the fibre-optical train. This happens due to the extreme conditions that occur during the operation of a material saturable absorber leading to modification of the material's properties. Additionally, it is not always possible to reproduce exactly the positioning of such an absorber within a fibre-optical system (e.g. how to reproduce the clamping force between two fibre ferrules and so forth). As a result, material-based saturable absorbers, just like fibre-optical polarisation controllers, are suitable for short demonstrations, for research activities, or for proof of concept using a certain effect. However often used in research practice, these elements do not meet the requirements exacted of commercial products that have to deliver reliable and reproducible long-term operation. Nevertheless, both fibre-based polarisation controllers and material-based saturable absorbers may be sometimes seen in commercial products, which latter should be hence classed as laboratory prototype devices rather than actual end-user products.

2.3. Optical fibre without polarisation maintenance

Still another approach unfit for commercial products is utilisation of optical fibre that does not maintain polarisation (such as the classical single-mode SMF-28 optical fibre). Polarisation state of radiation inside such a fibre is affected by a host of parameters including those of mechanical action on the fibre (variation of bending and/or torsion), ambient parameters (changes in the external temperature, radiation parameters (fluctuations of the radiation intensity), and so on. The presence of optical fibre without polarisation maintenance precludes reliable and reproducible achievement of the desired generation regime because the radiation state may be unpredictable. This uncertainty is eliminated by the use of polarisation-maintaining optical fibre.

All-fibre configurations using polarisation-maintaining fibre come the closest to meeting the expectations of the users who demand that fibre-optical technologies bring substantial improvements in comparison with the traditional volumetric laser devices. Introduction of discrete volumetric elements into fibre-optical systems departs from the attractive all-fibre concept and places such configurations into the hybrid category where it is necessary to maintain optimal optical alignment and cleanness of such elements. Among such elements one may list diffraction gratings commonly used for pulse compression or spectral selection in Piche [4] / Mamyshev [5] configurations and other elements. Hybrid layouts are popular in experimental research and their emergence was partly due to the fact that not all the necessary volumetric elements have their fibre-optical version and that some of these volumetric elements are considerably more affordable. In spite of this, such solutions are not very popular in commercial products and active efforts are under way to find fully fibre-optical replacement.

2.4. Selection of the desired generation regime among the available ones

Certain fibre laser configurations support multiple generation regimes, in which the output pulse parameters may drastically differ [6–9]. For selection of the desired generation regime in such cases, it is customary to compile so-called maps of generation regimes [10–12], which indicate the combination of the laser parameters and ambient conditions necessary for initiation of a specific regime. Ambient conditions (for instance, temperature) may vary, this is why the generation regime maps need periodic updates. Compilation of such a map requires some time and availability of specific measurement equipment (auto-correlator for monitoring the duration of ultra-short pulses, fast oscilloscope, and so on). The required time and equipment may not be readily available, thus rendering impossible compilation of generation regime maps. In such cases, the preference is given to those solutions that do not rely on maps of generation regimes, but instead support one only generation regime with the required parameters of the output pulses.

2.5. Radiation feed-back protection

Fibre delivery of output radiation has both advantages and drawbacks. Among the advantages one may list the possibility of radiation delivery to almost any point within the limits of the output fibre length and stable parameters of the output beam. The drawbacks include back-reflection of radiation, which may arise from reflection of the output radiation back into the fibre or due to the output fibre damage (again, a portion of the output radiation is returned back into the output fibre). In research installations, the effect of back-reflection is usually ignored [13–16], since it is considered an unlikely event. However, in the real-life operation of fibre lasers, back-reflection cannot be regarded as an exotic thing and it is necessary to study it and/or protect the equipment from it, for example, by inserting an optical diode (which may lead to a change of the output pulse parameters). Traditionally, protection from back-reflected radiation is not included into the scope of experimental systems (and even sometimes in end-user devices), but this problem exists and solutions to it should be considered in the course of research and development.

3. DISCUSSION

Non-polarisation-maintaining fibre is often combined with one or multiple polarisation controllers in order to create an artificial saturable absorber [17] for radiation mode locking [18]. In research practice, this approach is justified, but hardly in end-user systems because of constantly required adjustment of the polarisation controller(s), especially that the algorithm of this adjustment is not well understood. Machine-learning-aided adjustment of the polarisation state of radiation within such lasers requires significant time and equipment for monitoring of the output pulse parameters [19]. This approach, therefore, may be adequate in research and development, but its advantages in application to practical systems are far from obvious.

The number of possible material-based saturable absorbers grows every year [20–22] and many of them are attractive because of affordability and simplicity of use. The general problem of research into properties of these absorbers, however, is the absence of studies of their long-term stability. Saturable absorbers are operated under conditions close to extreme, which causes deterioration of their parameters [3]. This is true of both semiconductor absorbers and those based on other materials. Because of unknown working life time, these absorbers are the weakest elements in fibre-optical systems. Relatively short-term in-principle demonstration of their feasibility does not permit estimation of the prospect of their long-term use.

Compilation of generation regime maps (dispersion maps [23] and so forth) helps in research activities, but significantly complicates a commercial system. It must be also remembered that not all the available generation regimes may be used. Besides, re-compilation of such a map requires special measurement equipment for characterisation of the output pulse parameters. Instead of making operation of the mode-locked laser easier, regime maps rather make it more complicated.

Protection from back-reflection into the output waveguide is practically ignored when generation properties of mode-locked fibre lasers are studied, since in experimental research this effect (radiation coming back into the laser through the output waveguide) occurs quite infrequently. It is also rare in end-user systems, but such an occurrence may destroy the system completely. The likely destructive consequences of this effect deserve dedicated research efforts and consideration of measures of protection against it.

CONCLUSION

Analysis of certain approaches often resorted to in research practice of short-pulsed fibre-optical systems leads one to the conclusion that such systems may be divided into two categories: research systems (demonstration of effects or principles accompanied, as a rule, by the absence of any efforts in the area of reliability and working life time) and end-user systems (reliability and life time are among the most important parameters). In many published works, these two classes are mixed up and conclusion is drawn about significant potential of research systems, even though subsequently these systems may never enter the user space. The main reason of this stems from the solutions discussed in the foregoing sections. For end-user short-pulsed systems, the most desirable are all-fibre configurations whose design also includes solely PM optical fibre and artificial saturable absorbers. It is in those systems that the potential advantages of short-pulsed fibre-optical devices may be realised most fully.

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