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ABSTRACT

We present results on observation of real-time spectrum of the generation of the random fiber laser by using a technique of optical heterodyning in real-time.

Keywords: real-time measurements, Random lasers, fiber lasers

1. INTRODUCTION

Random distributed feedback fibre lasers are well known type of fiber lasers where the optical feedback is organized via amplified Rayleigh scattering on random in space sub-micron refractive index inhomogeneities. Random distributed feedback fiber lasers found their applications in telecommunications and distributed sensing systems, as well as attracted considerable amount of interest from researches. It is well-known that the generation spectrum of random distributed feedback fiber laser is a wide spectrum of typical width of 1 nm. It can be specifically tailored to demonstrate multi-wavelength, tunable operation etc. However, the main features of the generation spectrum should be defined by the nature of the feedback itself. Usually the smooth bell-shaped spectrum is attributed to the incoherent nature of the feedback. It is well known however that the Rayleigh scattering is an elastic scattering and should be resulted in the coherent feedback, which in turn leads to narrow features in the generation spectrum. Recently, narrow modes have been observed in the generation of the random distributed feedback fiber laser by means of scanning Fabry-Perot interferometer. The spectral width of modes was about tens of picometers and was limited by the spectral resolution of the scanning interferometer. Those modes were attributed to the stimulated Brillouin scattering.

In this work we present results on observation of real-time spectrum of the generation of the random fiber laser by using a technique of optical heterodyning in real-time. We found that in generation narrow modes could exist with a spectral width well below 100 kHz. Such spectrally localized states could be indication of coherent nature of the feedback.

2. EXPERIMENTAL TECHNIQUES

First we implemented the method of measuring the instantaneous generation spectrum based on heterodyning of the initial signal and subsequent post-processing of the signal to extract spectral information. An essential point for detecting narrow spectral components whose generation is unstable in time is the recording of long traces (from 100 million up to 1 billion points) with subsequent detailed spectral analysis at different frequency resolutions. For this, we created a software package that allows us to analyze the measured heterodyne signals. The developed module carries out the short-time Fourier transform of large data arrays with arbitrary window durations, the time shift of the window and an arbitrary window function. The operation of the software module was verified by a numerical experiment. As the window size increases, the spectral pattern “spreads out”. We made sure that to obtain an image of the dynamics with the best spectral resolution, it is necessary to use window durations of the order of a tenth of the characteristic time of the spectrum oscillation. The time step for conducting the moving Fourier transform can be chosen on the order of a hundredth of the characteristic time of the oscillation of the spectrum, a further decrease in the step time is pointless, since the window size becomes significantly larger than the step size, and the time resolution begins to be limited to it.
Further, we conducted an experimental verification of heterodyning setup. A series of experiments was conducted to study the local oscillator signal from narrow-band sources with known parameters. This made it possible, firstly, to verify the implementation of the heterodyning method, and secondly, to study the parameters of single-frequency lasers available in the local oscillators and to determine the most suitable ones for use in an experiment for recording unknown dynamics of a fiber laser. We examined several single-frequency laser sources of various types: a PurePhotonics PPCL550 semiconductor laser (instantaneous line width of the order of 10 kHz), Apex technologies TLS (instantaneous line width of the order of 3 MHz). Both lasers operate at a wavelength near 1550 nm and have the ability to tune.

Optical beat signals between two laser sources were measured using a four-port fiber coupler with a 50% coupling ratio, a polarization controller to match the polarizations of both lasers, a fast photodiode (Thorlabs DET08, 5 GHz, or u2t 50 GHz) and a broadband oscilloscope.

Analysis of the heterodyne optical beat signal between the Pure Photonics laser and the Apex TLS laser showed that there is a significant mutual wavelength drift (Fig. 1). The measurement duration was 400 µs with a sampling step of 0.4 ns, the window duration during processing was 2 µs, and the step was 0.2 µs. The characteristic drift is of the order of 40 MHz at times of the order of 200 µs. The slope of the curve is presumably due to the instability of the Apex TLS laser. To confirm the assumption about the main contribution of noise from the Apex TLS laser, we measured the effective line width of the PurePhotonics laser in a self-heterodyning setup with a short delay line in which the laser radiation is interfering with itself, but shifted to a certain frequency using an amplitude modulator. The measurement results showed that the effective width of the PurePhotonics laser generation line is only 3-4 MHz at times on the order of a second. Thus, this particular laser is suitable for performing heterodyne measurements. A separate advantage of this laser can be called a high output power - up to 18 dBm (80 mW). Thus, this laser can be used to study the features in the spectrum of a random laser with a spectral width of up to 10 kHz, however, during the measurement time of ~ 100 ms, the laser wavelength can drift within a few MHz, which can complicate the measurement of the fast dynamics of localized spectral modes.

![Figure 1. Spectrogram of signal beating between radiation of two single-mode semiconductor lasers: PurePhotonics PPCL550 and APEX TLS.](https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie)
The second stage of the work was the development of an experimental prototype of a Raman fiber laser with random distributed feedback, which allows measurements of spectrally localized states. As an active medium, 40 km of Corning SMF-28 fiber, a standard telecommunication fiber, was used. This fiber is characterized by an anomalous dispersion of about 16 ps / (nm*km) and Kerr nonlinearity of the order of 1/(W*km). A commercially available quasi-CW Raman laser with a fiber output was used as a pump laser. The pump laser radiation wavelength was 1455 nm, the lasing power could be set in 0.1 W steps in the range up to 5 W. The pump was introduced into the fiber through a wavelength-divison multiplexer to eliminate spurious back reflection, which threatened to damage the pump laser. There were no Bragg fiber gratings in the circuit, so that the lasing in the fiber occurred in one pass due to amplification of radiation at a wavelength of about 1555 nm due to stimulated Raman scattering (SRS). The generation wave, co-directional with the pump wave, propagated to the exit from the fiber, where it passed through a second coupler with wavelength separation to separate the pump radiation, which could remain unabsorbed. Next, an optical isolator was put to exclude back-reflection from measuring equipment, which may play the role of spurious feedback and change the nature of generation. The generation wave propagating in the opposite direction went into the fiber ring mirror located at the opposite end of the fiber and returned to the fiber. Thus, the feedback was realized by the Sagnac fiber mirror on the one hand and random feedback due to Rayleigh scattering in the fiber on the other hand (see Fig. 2).

The laser radiation at the output of the laser was divided using a fiber coupler in a ratio of 99:1 and sent to a photodetector and spectrum analyzer. A spectrum analyzer with a resolution of 0.02 nm was used to control the shape and width of the generation spectrum. The laser generation threshold was 1.3 W. With a pump power of 3.2 W, the generation power was 205 mW. High above the lasing threshold, the radiation power increases linearly with the pump power. In this case, stochastic noise is observed in the measured generation spectrum due to rapid fluctuations of the total power during the measurement of the spectrum analyzer. Such fluctuations are usually associated with the development of the nonlinear stimulated Brillouin scattering (SBS) process inside the resonator. The width of the laser generation spectrum at the 3 dB level turned out to be almost independent of power and was of 1.4 nm, which is equivalent to 175 GHz for the studied wavelengths.

The total intensity of the output radiation randomly fluctuates at small time scales (determined by the spectral band of the oscilloscope). Moreover, if we construct the temporal dynamics of the intensity over the entire measured range, then it turns out to be very heterogeneous. At small times of the order of the sampling step, the intensity everywhere randomly fluctuates in time, but at times of the order of milliseconds there are areas where its change is quite smooth. This is especially clearly seen when averaging the entire measured signal, at which N neighboring points were replaced by one average value. In this case, high-frequency fluctuations were smoothed out, and the graph of the dependence of the averaged intensity on time in individual sections turned out to be smooth. Such instability may be due to the SBS effect. It is known external perturbations, for example, acoustic noise, may lead cascade SBS processes to be broken, that in turn may lead to a decrease in noise of full intensity, and the appearance of smooth dynamics of full intensity. After some time, the effects of SBS can develop again - and high-frequency modulation reappears in the temporal dynamics.
The width of the lasing spectrum is an order of magnitude greater than the spectral band of the oscilloscope, which makes it impossible to register the temporal dynamics of the heterodyne signal without distortion. In this case, two methods can be implemented to measure the spectral characteristics of the radiation. The first involves the use of a spectral filter that cuts off part of the radiation from a random laser immediately before receiving a heterodyne optical signal. Filtering the optical signal to spectral widths of the order of the band of the oscilloscope (more precisely, half the band of the oscilloscope) will then make it possible to bring down such narrow-band radiation with the radiation of a local oscillator and to detect it without additional averaging by the measuring system.

The second method is to install a filter inside a random laser to obtain narrow-band lasing. The proper place within the cavity should be chosen where the radiation power is small. We have tested that in this case the laser emission spectrum narrows substantially and amounts to about 30 pm i.e. 4 GHz. The advantage of this method is that a narrow filter eliminates the development of the SBS process. Indeed, when scattering by longitudinal acoustic waves, the scattered radiation wavelength shifts by 10 GHz, i.e. the scattered wave is effectively cut off by the filter. This allows you to get a stable generation spectrum. Note that in the laser setup with a filter, due to additional losses introduced by the filter (of the order of 3-5 dB), the lasing threshold increased from 1.3 W to 1.6 W.

3. RESULTS

The first step was to study the spectrum of a Raman fiber laser with random distributed feedback with an optical filter. To obtain the optical beat signal, we used a local oscillator - a Tunics semiconductor laser with parameters similar to those of a PurePhotonics laser, whose radiation was interfered with the radiation from the laser using a 50/50 fiber coupler and a polarization controller. The beat signal was measured using a Finisar photodetector with a spectral band of 50 GHz, and an Agilent digital oscilloscope with a bandwidth of 33 Hz, sampling frequency of 80 GHz, and a sampling step of 12.5 ps. The maximum number of points that the oscilloscope could save in one measurement was 20 billion, which corresponded to a time interval of 25 ms.

![Figure 3. An example of a fast spectral dynamics of a random fiber laser measured with the method of heterodyning.](image-url)
The wavelength of the local oscillator was chosen so that the frequencies of the optical beats fell in the center of the frequency band of the measuring system. The optical power of the local oscillator and the laser power level, controlled by an additional fiber attenuator, were chosen to maximize the contribution of beats to the signal at the photodetector. To construct the spectrogram, a window with a duration of 1 µs was used. Localized features are detected in the spectrum (see Fig. 3). Note that such a fine structure of the spectrum was observed only with a slight excess above the threshold (the pump power in this experiment was 1.6 W). With an increase in the pump power up to 2 W, the peaks in the heterodyne spectrum disappeared, and the spectrum became smooth.

To verify the obtained spectra, the spectrum of the heterodyne signal and the spectrum of a random laser measured using a spectrum analyzer with a resolution of 20 pm were compared. For this, the heterodyne laser spectrum was constructed using a FFT window corresponding to a resolution of 20 pm (2.5 GHz) and averaged over the entire observation time (1 ms). Then, the spectral power density was converted into spectral power taking into account the sampling step along the wavelength. As a result, a qualitative and quantitative correspondence between the spectra was obtained.

Further, we showed that spectrally localized modes arise in random parts of the lasing spectrum. To this end, we performed a series of measurements of the short time dynamics of the heterodyne signal at arbitrary time intervals. Then, an instantaneous emission spectrum was constructed for each of the temporal speakers. Indeed, from measurement to measurement, spectral peaks arise in arbitrary parts of the spectrum. We have built a histogram of the positions of the peaks in the spectrum. As it turned out, it has a smooth shape without pronounced maxima and extends to the entire spectrum of laser generation.

It should be noted that the spectral modes also establish themselves in the radio-frequency spectrum that can be measured directly using rf-analyzer, or, in our case, with FFT of the long time dynamics. Such signal can be used to estimate the spectral width of each localized mode. We used the radio frequency spectrum calculated from the time dynamics of the total intensity of 10 ms duration. Such a duration provides a spectral resolution of 300 Hz (for a rectangular Fourier transform window). High intensity beating signal appears at random frequencies. Though, it was not possible to estimate the linewidth of the modes from this data.

4. CONCLUSION

We realized a method for measuring the instantaneous lasing spectrum and its dynamics with a frequency resolution of up to 1-10 kHz based on optical heterodyning with various types of local oscillators. Using a numerical experiment, as well as experimentally based on various laboratory sources of laser radiation, a cross-check of the spectrum reconstruction method was carried out. We found that there are narrow spectral modes in the radiation of random fiber laser operating in some range of output power. We also made first steps to determine the properties of the generation of localized components. It was experimentally shown that spectrally localized modes arise randomly over the entire lasing spectrum.

This work was supported by Russian Science Foundation (19-12-00318).

REFERENCES