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Self-mixing detection of backscattered radiation in a single-mode erbium fibre laser for Doppler spectroscopy and velocity measurements

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Abstract. **We report an experimental study of the self-mixing effect in a single-mode multifrequency erbium fibre laser when radiation backscattered from an external moving object arrives at its cavity. To eliminate resulting chaotic pulsations in the laser, we have proposed a technique for suppressing backscattered radiation through the use of multimode fibre for radiation delivery. The multifrequency operation of the laser has been shown to lead to strong fluctuations of the amplitude of the Doppler signal and a nonmonotonic variation of the amplitude with distance to the scattering object. In spite of these features, the self-mixing signal was detected with a high signal-to-noise ratio (above 10^2) when the radiation was scattered by a rotating disc, and the Doppler frequency shift, evaluated as the centroid of its spectrum, had high stability (0.15 %) and linearity relative to the rotation rate. We conclude that the self-mixing effect in this type of fibre laser can be used for measuring the velocity of scattering objects and in Doppler spectroscopy for monitoring the laser evaporation of materials and biological tissues.**

Keywords: *fibre lasers, self-mixing effect, autodyne effect, Doppler spectroscopy.*

1. Introduction

Radiation backscattered (back-reflected) from an external moving object initiates a self-mixing (autodyne) effect in lasers, which shows up as modulation of the laser light. In a number of instances, the effect is regarded as 'parasitic' because it disturbs the stable operation of the laser source. When the backscatter signal produces weak disturbances, the effect can be used for gaining information about an external moving object: in velocity measurements [1], detection of small vibrations [2], range finding [3] and Doppler spectroscopy studies of laser-induced mass transport processes [4]. The effect is used in creating surgical laser systems with feedback, which offer online noncontact control over the laser evaporation of biological tissues [5]. The self-mixing effect was observed and investigated in semiconductor [6], gas [1, 3], solid-state (Nd : YAG) [7] and other lasers.

In the last 10 – 15 years, the application area of fibre lasers has been considerably extended. They are widely used in materials processing and laser medicine owing to their high output powers (up to the kilowatt level) and high beam quality [8, 9]. Fibre lasers begin to be applied in velocity measurements and Doppler spectroscopy (with the use of optical heterodyning) [10]. To this end, use is typically made of single-mode, single-frequency lasers of low power (under 1 W). Application of fibre lasers in velocity measurements and Doppler spectroscopy in a self-mixing scheme has been the subject of few reports [11, 12]. At the same time, the use of this effect in fibre lasers may open up significant possibilities in a number of applications because the self-mixing scheme (also referred to as autodyne detection) is much simpler and does not require any additional optical components or a special optical layout. In particular, it is of interest to employ this effect for the online monitoring of laser processing of materials and for creating a feedback channel in surgical laser systems, like in the case of CO_2 lasers [4, 5].

Fibre lasers, however, have a number of inherent features that significantly influence the feasibility of employing the autodyne effect. First, they are very sensitive to backscattered radiation, which may lead to unstable laser operation. In a number of instances, to eliminate this parasitic effect, use is made of Faraday isolators, which block the backscatter signal. Second, such lasers are inherently multifrequency because they have a long cavity (2 – 10 m) in combination with a large gain bandwidth, which creates conditions for multiple longitudinal mode lasing. Third, a rather important factor in measurements via the autodyne detection of backscattered radiation is the amplitude noise in the laser: its magnitude and spectral range. These features raise the question of whether the self-mixing effect in fibre lasers can in principle be used in practical applications.

The purpose of this work was to study the self-mixing effect in a single-mode multifrequency erbium fibre laser and analyse the feasibility of using it in velocity measurements and Doppler spectroscopy.

2. Experiment

We used a 5-W single-mode multifrequency erbium fibre laser (IRE-Polus Science and Technology Association) operating at 1.54 μm. The distal part of the fibre had a collimator which formed a plane-parallel beam 2 mm in diameter. The laser included a Y coupler, which allowed part of the laser output to be directed to a photodetector in order to study noise characteristics of the laser and detect the beat signal resulting from the self-mixing effect. The attenuation in the coupler was 40 dB. The signal from the photodetector was amplified and fed to a computer-interfaced ADC to store it for further processing (Fig. 1).

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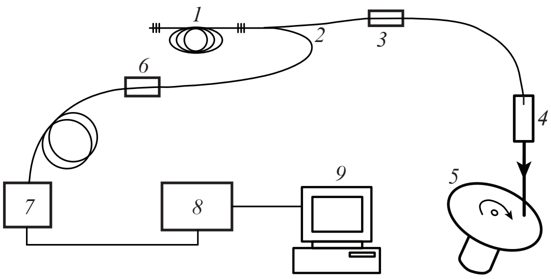

Figure 1. Experimental setup for studies of the self-mixing effect in a single-mode multifrequency erbium fibre laser: (*1*) laser; (*2*) Y coupler; (*3*, *6*) fibre-optic connectors; (*4*) collimator; (*5*) rotating disc; (*7*) photodetector; (*8*) ADC, (*9*) computer.

In our experiments, we measured the amplitude noise, long-term stability and optical spectrum of the laser output. The long-term stability of the output power, measured during 10 min of constant operation, was ± 5% of its average, and the amplitude noise at frequencies from 1 kHz to 1 MHz was ± 0.15%. Figures 2 and 3 show amplitude noise spectra of the laser at different output powers and three lasing spectra, measured with an OSA AQ6330 ANDO spectrum analyser. The width of the spectra was 0.5 nm. Note that the centre frequency and bandwidth depended only slightly on output power and that the spectrum had an unstable, fluctuating shape.

To examine the self-mixing effect in the fibre laser, a rotating disc was used as a backscattered radiation source. The laser was found to be rather sensitive to the backscatter signal. When light was scattered by the surface of the disc at rest or rotating at a small rate, the laser operated in a chaotic pulsed mode with 100% modulation. At high rotation rates and additional attenuation of the output laser beam, we observed a Doppler signal with a rather high signal-to-noise ratio. Figure 4 shows a typical autodyne signal spectrum obtained under such experimental conditions.

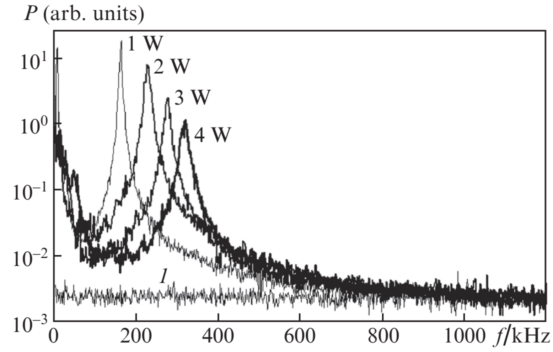

Figure 2. Amplitude noise power spectra of the single-mode erbium fibre laser at different output powers; (*1*) noise obtained with the laser turned off.

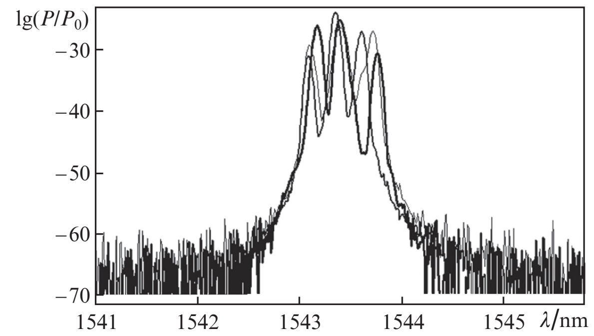

Figure 3. Optical emission spectra of the single-mode erbium fibre laser at an output power of 2 W.

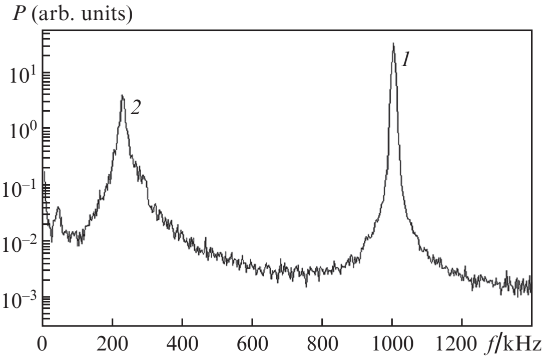

Figure 4. Power spectrum of the autodyne signal for laser radiation scattering by a rotating disc: (*1*) autodyne signal due to self-mixing between the frequency-shifted backscattered radiation and the output laser beam; (*2*) laser noise in the resonance region.

Such behaviour of the laser is associated with the resonant nature of its sensitivity to backscattered radiation, typical of class-B lasers [13, 14], which have relaxation oscillations (see below). The high sensitivity of the fibre laser at resonance disturbs steady-state lasing when the Doppler frequency shift falls within the resonance band. To eliminate chaotic pulsations, two techniques for attenuating backscattered laser radiation were tested. In one of them, we used a standard Faraday isolator which enabled light attenuation by 40 dB. In spite of the attenuation, an autodyne signal was detected. The spectrum of the signal was similar to that in Fig. 4, but with a lower signal-to-noise ratio. Since standard Faraday isolators have a large attenuation coefficient, we proposed and tested another backscattered radiation attenuation technique, which relied on the use of multimode fibre for delivering laser radiation to a target [15]. In this case, the main radiation delivered to the target has low losses, whereas the scattered radiation that reaches the laser cavity is highly attenuated because only a small part of the backscatter signal emerging from the multimode fibre is coupled into the single-mode fibre of the laser. This backscatter signal attenuation technique has the advantage of simplicity, with the possibility of easily varying the attenuation level according to the initial backscattering level.

Figure 5 shows the power spectrum of the autodyne signal for laser radiation scattering by a rotating disc and attenuation by multimode fibre. The spectrum is strongly broadened compared to the spectra obtained without attenuation or with the use of a Faraday isolator. The cause of the broadening is that the beam emerging from the multimode fibre has large divergence, so the collective angular aperture considerably exceeds that in the case of a parallel beam emerging from a collimator. As a result, radiation directed at various angles to the velocity vector of the disc surface is detected.

The two attenuation techniques were found to enable detection of the signal from the rotating disc over the entire

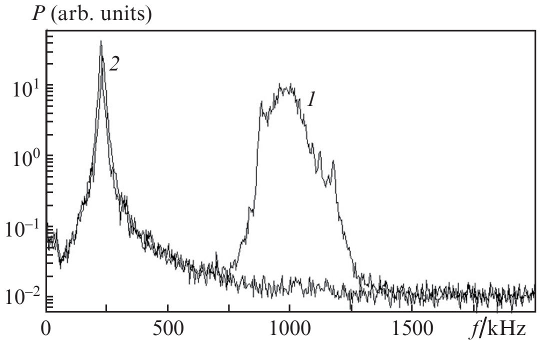

Figure 5. Power spectrum of the autodyne signal for laser radiation scattering by a rotating disc and beam delivery through multimode fibre: (*1*) autodyne signal due to self-mixing between the frequency-shifted backscattered radiation and the output laser beam; (*2*) laser noise in the resonance region.

frequency range, including the narrow resonance band, without disturbing laser operation. In spite of the strong attenuation, the signal-to-noise ratio was large enough to detect the signal from the rotating disc at Doppler frequency shifts of up to 1.5 MHz, corresponding to velocities of up to 1 m s^{-1}. It is worth noting that, when high velocities should be measured, this range can be markedly extended. It is sufficient not to attenuate the backscatter signal: the sensitivity will then increase by about four orders of magnitude and, hence, the frequency range of the detected signal will be extended.

The amplitude of the observed autodyne signal was found to strongly fluctuate (the amplitude varied by more than ten times) (Fig. 6). The observed Doppler signal power fluctuations were obviously of a nonstationary nature. The fluctuation frequency was tens of hertz immediately after the laser was turned on, and decreased during the operation of the laser, down to a fraction of a hertz after 2 min of constant operation. Figure 7 illustrates the dynamics of a weighted-average autodyne signal frequency $\bar{f}_{\rm D}$ (calculated in the frequency range 500–1500 kHz) for laser radiation scattering by the rotating disc. It is seen that the frequency thus measured is rather stable, despite the strong Doppler signal amplitude fluctuations (Fig. 6). The rms deviation of the weighted-average frequency from the average value was 1 kHz, which corresponded to a 0.1% accuracy in our Doppler frequency shift measurements for scattering by the rotating disc.

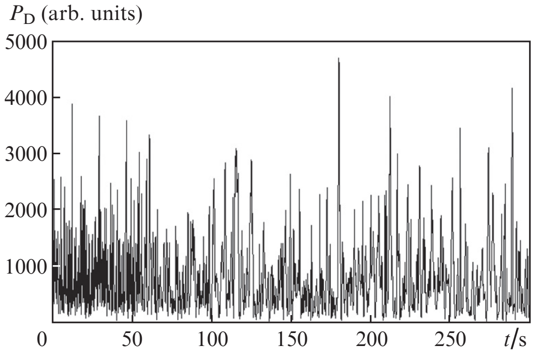

Figure 6. Time variation of the autodyne signal power for laser radiation scattering by a rotating disc.

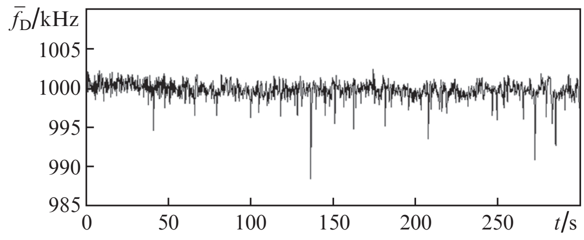

Figure 7. Dynamics of a weighted-average autodyne signal frequency for laser radiation scattering by the rotating disc.

The Doppler frequency shift $f_{\rm D}$ determined using optical heterodyning [10] and the linear velocity v of a scattering object along the probing axis are related by $f_{\rm D} = 2v/\lambda$, where λ is the laser radiation wavelength. This relation is basic to classic velocity measurement techniques. In our experiments, the Doppler frequency shift was evaluated from the beat frequency of the laser radiation. In contrast to optical heterodyning, this signal originates from the influence of backscattered laser radiation on the lasing process. In this connection, it was of interest to find out to what extent the measured frequency was linear with disc rotation rate. To this end, the Doppler frequency shift was plotted against disc rotation rate (Fig. 8). As a scatterer, we used a disc with 64 slits, with a built-in light emitting diode (LED) and a photodetector, which detected the optical signal coming from the LED. The disc rotation rate was $f_{\rm rot} = f_{\rm s}/64$, where $f_{\rm s}$ is the frequency of the signal from the photodetector. The error of determination of $f_{\rm rot}$ was 0.2%. From $f_{\rm D}(f_{\rm rot})$ data, we obtained a best fit straight line by least squares fitting. The measured $f_{\rm D}$ values deviated from the least squares straight line by no more than 0.3%.

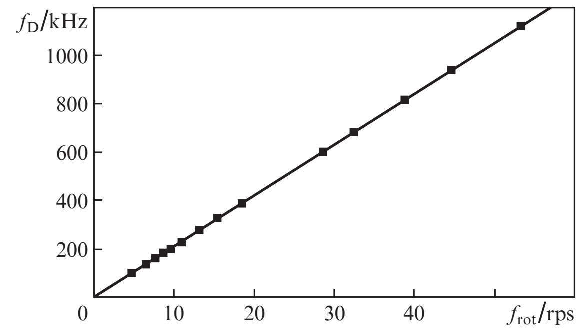

Figure 8. Doppler frequency shift (centroid of the autodyne signal spectrum) as a function of disc rotation rate. The solid squares represent the experimental data and the solid line represents the least squares straight line.

We measured the average autodyne signal power (averaging time, 1 min) as a function of the distance from the collimator to the surface of the rotating disc, $l_{\rm d}$ (Fig. 9). The beam was not focused, so the backscattering level would be expected to decrease quadratically with increasing distance. This would lead to a quadratic dependence of the autodyne signal power because, in the case of linear autodyne detection, the signal power is proportional to the backscattered radiation power [14]. As seen in Fig. 9, this dependence is clearly nonmonotonic, with a maximum at $l_{\rm d} \approx 45$ cm.

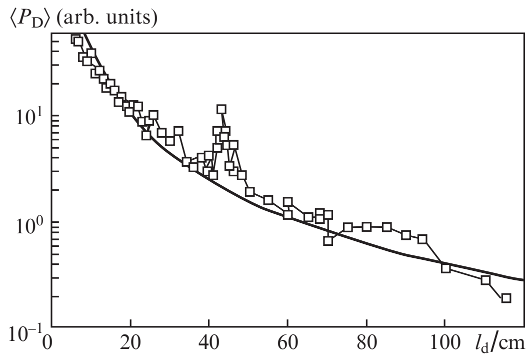

Figure 9. Average autodyne signal power (averaging time, 1 min) as a function of distance from the collimator to the surface of the rotating disc. The open squares represent the experimental data and the solid curve represents the inverse quadratic relation $4000/l_\mathrm{d}^2$. The Doppler frequency shift is $f_\mathrm{D} = 250$ kHz.

3. Discussion

Self-mixing is due to two processes: the mixing of backscattered radiation with the laser output and the amplification of the radiation that has reached the laser cavity. The amplification of the radiation leads to a dependence of the autodyne signal amplitude on the Doppler frequency shift of the backscattered radiation: the amplitude–frequency response (AFR) of autodyne detection. The dependence for class-B lasers has a resonant nature, with a maximum at the relaxation frequency of the lasers [13, 14]. The sensitivity of such lasers to backscattered radiation in the resonance region may considerably exceed that ensured by conventional heterodyning. The autodyne gain, which characterises the ratio of the autodyne and heterodyne signals under identical conditions, may reach 100 and more [14]. This accounts for the high sensitivity of the fibre laser to backscattered radiation.

Since the laser used was multifrequency, this determines a number of additional features of the self-mixing effect, which were observed in our experiments. Consider first the large fluctuations of the autodyne signal (Fig. 6). In general, Doppler signal fluctuations in the case of scattering from the surface of a rotating disc are a normal effect, which is typically caused by inhomogeneity of the disc, as a result of which backscattered radiation produces a three-dimensional speckle structure, which varies during disc rotation. However, the fluctuations observed in our experiments cannot be accounted for by the formation of a speckle structure. First, the Doppler signal fluctuations caused by the speckle structure of the backscattered radiation should be considerably weaker than the average signal power level, because the average speckle size is far smaller than the collective aperture ($D = 2$ mm). Indeed, the average speckle size ε at the collimator output can be estimated using the formula [16]

$$\varepsilon \approx 3\lambda l_\mathrm{d}/D \approx 0.2\ \mathrm{mm}, \tag{1}$$

where the distance from the collimator to the surface of the rotating disc is $l_\mathrm{d} = 10$ cm. Second, such fluctuations would be expected to have a chaotic steady-state nature, but in our experiments their frequency varied from tens of hertz to a fraction of a hertz after several minutes of constant laser operation. Thus, the observed fluctuations of the power of the Doppler signal detected using self-mixing are due to the internal dynamics of the multifrequency fibre laser.

Another feature is the nonmonotonic variation of the autodyne signal power with distance to the surface of the rotating disc (Fig. 9).

It can be shown that these two factors in the behaviour of the autodyne signal in the fibre laser are related to specific features of the interference of multifrequency laser radiation. The signal power at the photodetector (with no allowance for the AFR of autodyne detection) for the mixing of the main and backscattered radiation can be written as

$$P = S\Big\langle\Big|\sum_j E_j\exp[-\mathrm{i}(\omega_0 + j\delta)t] + \beta\sum_m E_m\exp\Big[-\mathrm{i}(\omega_0 + m\delta)\Big(t - \frac{z}{c}\Big)\Big]\Big|^2\Big\rangle, \tag{2}$$

where the parameter S depends on the sensitivity of the photodetector; $E_{j(m)}$ is the electric field amplitude in the jth (mth) longitudinal mode; β is the amplitude backscattering coefficient; δ is the intermodal frequency spacing; c is the speed of light; $z = 2l_\mathrm{d}$ is the path difference between the main and backscattered radiation; and ω_0 is the centre frequency of the laser radiation. The averaging time in (2) is considerably longer than the period of optical oscillations $2\pi/\omega_0$ and the intermodal beat period $2\pi/\delta$.

From (2), we find the Doppler signal power (variable component) in the form

$$P_\mathrm{D} = 2S\Big\langle\mathrm{Re}\Big(\beta\sum_j E_j\exp(-\mathrm{i}(\omega_0 + j\delta)t) \times\sum_m E_m^*\exp\Big[\mathrm{i}(\omega_0 + m\delta)\Big(t - \frac{z}{c}\Big)\Big]\Big)\Big\rangle = 2S\beta\,\mathrm{Re}\Big[\exp\Big(-\mathrm{i}\omega_0\frac{z}{c}\Big)\sum_j|E_j|^2\exp\Big(-\mathrm{i}j\delta\frac{z}{c}\Big)\Big]. \tag{3}$$

In (3), we take into account that, when averaged over a time considerably longer than the intermodal beat time, the E_jE_m products with $j \neq m$ give zero. The first term in the product in the final expression in (3) represents beats at the Doppler frequency when the object moves at velocity v, i.e. at $z = 2(l_\mathrm{d} + vt)$. The second term determines the amplitude of the Doppler signal, which is a slower function of distance z than is the first term because $j\delta \leqslant \Delta\omega = \delta n_0 \ll \omega_0$, where $\Delta\omega$ is the laser emission bandwidth and n_0 is the number of generated longitudinal modes. Thus, the second term represents the dependence of the Doppler signal amplitude on the distance to the target, l_d. This dependence is periodic, with a period $l_0 = L$, where L is the cavity length.

At $l_\mathrm{d} = nl_0$, where $n = 0, 1, 2, 3\ldots$, the signal will have maxima, because all the interfering longitudinal modes will have a phase shift of 2π. This accounts for the nonmonotonic decrease in autodyne signal power with increasing distance to the disc surface. The maximum at $l_\mathrm{d} \approx 45$ cm is most likely related to the first maximum ($n = 1$) in the periodic dependence in question.

It also follows from (3) that the forming multifrequency laser radiation mixing signal may also fluctuate in amplitude. Indeed, the second term in (3), which determines the Doppler signal amplitude, contains the intensity ($|E_j|^2$) of each longitudinal mode. When the laser emission spectrum has an unstable shape, as observed in this study (Fig. 3), the intensity of each mode is time-dependent, $|E_j(t)|^2$, which eventually leads to Doppler signal amplitude modulation. It is worth noting that, according to (3), multifrequency operation of the fibre laser influences only the amplitude of the observed signal, whereas the Doppler shift itself remains constant at $2\omega_0 v/c$. High stability (~0.1%) of the weighted-average frequency of the autodyne signal spectrum was observed experimentally by us. The linear dependence in Fig. 8 also suggests that the self-mixing in the multifrequency fibre laser does not distort the measured Doppler frequency shift.

Despite the above features of the self-mixing effect, the low coherence and the extremely high sensitivity of the erbium fibre laser to backscattered radiation, we believe that this type of laser can be used in velocity measurements via the autodyne detection of backscattered radiation. In addition, such lasers have a relatively high output power, which offers the promise of employing the self-mixing effect in laser surgery for noncontact online monitoring the laser biological tissue destruction process, like in the case of CO_2 lasers [4, 14]. In these applications, a key role is played not by the amplitude of the autodyne signal but by its spectrum, which determines the velocity of a scattering object or mass transport processes in the laser-exposed zone of a scattering medium.

4. Conclusions

We have studied the self-mixing effect in a single-mode multifrequency erbium fibre laser from the viewpoint of using it in velocity measurements and Doppler spectroscopy. To eliminate chaotic pulsations in the fibre laser, we have proposed a technique for suppressing backscattered radiation through the use of multimode fibre for radiation delivery. This technique allows us to find conditions for stable steady-state lasing, which, at the same time, enable the self-mixing Doppler signal to be detected with a high signal-to-noise ratio.

The multifrequency operation of the laser used is shown to lead to strong fluctuations of the Doppler signal and a nonmonotonic variation of its amplitude with distance to the scattering object. In spite of these features, the signal can be detected with a high signal-to-noise ratio and the Doppler frequency shift, evaluated as the centroid of its spectrum, has high stability (0.1%) and linearity (0.3%) relative to the disc rotation rate. Thus, under the conditions of our experiments, the uncertainty in velocity measurements was 0.3%.

This leads us to conclude that the self-mixing effect in the type of laser in question can be used for velocity measurements and online monitoring of laser-induced mass transport processes.

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