*LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS*

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# Experimental investigations of the influence of a tapered fibre on the stability of the intermode frequency of highly stable femtosecond pulses

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***Abstract*. The experimental procedure and the results of high-precision measurements of the intermode frequency of a femtosecond Ti : sapphire laser at the output of a tapered fibre are described. In the process of mode transformation, the stability of the intermode frequency is shown to degrade roughly by a factor of 2 for short averaging time intervals (10 s) and by a factor of 1.1 for long averaging time intervals (1000 s).**

***Keywords***: *femtosecond laser, optical fibre, frequency stability.*

The development of fibreoptic systems for the broadening of femtosecond frequency combs based either on holey fibres [1, 2] or tapered fibres [3, 4] opens up a unique opportunity to synthesise and measure frequencies ranging from the radio-frequency to the UV region. As a femtosecond pulse propagates through such fibres, the mode spectrum can broaden by more than an octave. Because of nonlinear properties of the fiber material, the propagation of a high-intensity pulse is accompanied by the cross-phase modulation of modes. This leads to the formation of sidebands with a separation exactly equal to the intermode frequency interval, thus forming a broadened spectrum.The intensity envelope of the spectrum may have a complicated shape in this case.

Much effort is now concentrated on studying the physics behind frequency conversion in fibreoptic systems, including, in particular, the nature of the nonlinearity responsible for spectral broadening, as well as the properties of output radiation. The key question is whether a train of highly stable femtosecond pulses passing through the fibreoptic system still has a stable intermode frequency. Other questions are what amplitude – frequency characteristics the output radiation has and how the energy is redistributed between the components of the converted radiation.

In this work, we have experimentally investigated the stability of the intermode frequency of a highly stable femtosecond Ti : sapphire laser at the output of a tapered fibre. The experimental procedure included the measurement of the stability of the intermode frequency of the femtosecond Ti : sapphire laser (with a pulse repetition rate of 100 MHz) at the input and output of the fibre. With the help of bandpass filters, we have also separated two spectral regions of output radiation and measured the stability of intermode beats within them.

To perform these high-precision measurements, we have developed and created a device whereby the intermode frequency was mapped onto the low-frequency region, where high-precision measurements of the selected frequency (200 Hz) were then carried out. A detailed description of this device will be provided elsewhere.

The experiment consisted of two stages. At the first stage, we investigated the intrinsic frequency noise of the device using an external reference of time scale, i.e., using a signal from a hydrogen frequency standard instead of the intermode frequency of the laser. These investigations showed that, for the averaging time of $10^2 - 10^3$ s, the developed device performed measurements with a relative precision of $10^{-14} - 10^{-15}$.

At the second stage, we examined the stability of the intermode frequency $f_{\rm m}$ of the highly stable femtosecond Ti : sapphire laser described in our earlier work [5]. (The stability of an unstabilised laser was several orders of magnitude lower, which prevented us from using this laser for the above-mentioned investigations.) The tapered fibre was fabricated at the University of Bath (United Kingdom) from Corning SMF-28, standard telecommunication fibre with a core diameter of 9 μm. The cutoff wavelength of the second fibre mode was 1250 nm. We used a fibre with a waist diameter of 2.5 μm and a waist length of 60 mm. The power of radiation coupled into the fibre was about 170 mW. The spectrum of output radiation spanned from 400 up to 1200 nm. We performed a series of measurements of the stability of the intermode frequency for different averaging time intervals at the input and at the output of the fibre. The results of these studies are summarised in Table 1.

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**Table 1.**

| Averaging time/s | Average frequency/Hz | | Root-mean-square frequency deviation/Hz | | Number of measurements | | Relative stability of the frequency $\Delta f_m/f_m$ | |
|---|---|---|---|---|---|---|---|---|
| | at the input | at the output | at the input | at the output | at the input | at the output | at the input | at the output |
| 1 | 199.999386 | 199.999268 | $2.901 \times 10^{-3}$ | $5.744 \times 10^{-3}$ | 1200 | 1183 | $2.9 \times 10^{-11}$ | $5.744 \times 10^{-11}$ |
| 10 | 199.999762 | 199.999184 | $4.280 \times 10^{-4}$ | $8.016 \times 10^{-4}$ | 180 | 198 | $4.280 \times 10^{-12}$ | $8.016 \times 10^{-12}$ |
| 100 | 199.999855 | 199.999876 | $5.738 \times 10^{-5}$ | $6.940 \times 10^{-5}$ | 98 | 92 | $5.738 \times 10^{-13}$ | $6.940 \times 10^{-13}$ |
| 1000 | 199.999949 | 199.999976 | $4.824 \times 10^{-6}$ | $5.411 \times 10^{-6}$ | 12 | 13 | $4.824 \times 10^{-14}$ | $5.411 \times 10^{-14}$ |

**Table 2.**

| Parameters of radiation | Number of measurements | | |
|---|---|---|---|
| | At the input of the fibre | With an SS4 filter | With an SZS5 filter |
| | 98 | 83 | 92 |
| Average value of measured frequency/Hz | 199.999855 | 199.999846 | 199.999876 |
| Root-mean-square frequency deviation/Hz | $5.738 \times 10^{-5}$ | $8.458 \times 10^{-5}$ | $6.940 \times 10^{-5}$ |

Note: the averaging time is 100 s.

One can see from Table 1 that the stability of the frequency $f_m$ is approximately an order of magnitude lower than the stability limit of our measuring system. Propagation of radiation through the fibre slightly lowers the stability of $f_m$, which is, apparently, due to the increase in phase fluctuations. For short averaging time intervals, the stability of $f_m$ at the output of the fibre is approximately two times lower than the stability at the input of the fibre. For long averaging times (1000 s), the stability remains virtually unchanged.

In our further studies, we explored whether the stability depends on the spectral range of measurements. To examine this problem, we divided the whole spectral range into two subranges by using bandpass filters (an SS4 filter was used to separate the spectral region from 700 up to 1200 nm, while an SZS5 filter separated the region from 400 up to 600 nm). The average frequency was then measured at the output of the fibre within each of these subranges. The results of these measurements are summarised in Table 2. The results of frequency stability measurements at the input of the fibre are also given for comparison. One can see from Table 2 that the stabilities of $f_m$ differ for different regions of the broadened spectrum.

We can conclude that the nonlinear mode transformation (cross-phase modulation) accompanying the propagation of trains of highly stable femtosecond pulses through a tapered fibre results in a certain degradation of the stability of the intermode frequency. This effect can be explained by the presence of weak amplitude–frequency fluctuations of radiation in the fibre and by the incomplete averaging of these fluctuations during the measurement.

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