

Wavelength and line width measurement of optical sources with femtometre resolution

Th. Schneider

A new and very simple method for the wavelength and line width measurement of optical sources with a resolution in the femtometre range is presented. Our method is based on the amplification of a backscattered wave by a pump wave due to Brillouin scattering. It requires neither a fast photodiode nor a spectrum analyser of any kind.

Introduction: The determination of the wavelength and bandwidth of an optical source is very important in science and technology. Commonly, spectrometers are used for this purpose. In the field of optical telecommunications the spectrum can be measured by an optical spectrum analyser, for instance. These devices offer a quick overview over a relatively large wavelength range. However, they have a rather low resolution of only ≈ 0.1 nm, which corresponds to ≈ 12.5 GHz at a wavelength of 1550 nm. In [1] a wavelength measurement method with femtometre resolution was presented. The approach in [1] relies on the high resolution of a Fabry-Perot interferometer. The frequency dependence of Brillouin scattering was exploited to distinguish between different fringe orders.

For the measurement of the bandwidth of an optical source the so-called 'self-delayed heterodyne beating' [2] can be used. This method transforms the optical bandwidth into the electrical domain by the beating between the delayed signal and a frequency shifted copy of the signal in a photodiode. The result can be measured by a radio frequency spectrum analyser. The idea was expanded for the simultaneous measurement of multichannel laser line widths and spacing by Lyu *et al.* [3]. For this method the frequency shift will be carried out by stimulated Brillouin scattering in an optical fibre. Different channels can be distinguished owing to the dependence of the Stokes frequency shift on the pump wavelength.

In this Letter we present a very simple method with which not only the bandwidth but the absolute wavelength can be determined with a resolution in the femtometre range as well. The method requires neither a fast photodiode nor a spectrum analyser of any kind.

Brillouin scattering: The basic idea of our method is that the unknown wavelength of a probe can be measured by the known wavelength of a pump via Brillouin scattering (BS) in an optical fibre. Stimulated Brillouin scattering is an interaction between the intense optical field of a pump wave and an induced electrostrictive acoustic wave in the fibre. It is the nonlinear optical effect with the smallest threshold. Only a few milliwatt of optical power are sufficient for the generation of a stimulated backscattered Stokes wave. Because of the relative velocity between the pump and the acoustic wave the Stokes wave is downshifted in frequency. The frequency shift between pump and Stokes wave depends on environmental conditions, such as temperature and strain, on the waveguide characteristics and on the pump wavelength. For our standard singlemode fibre (SSMF) we measured in a loop arrangement, described below, a frequency shift of 10.724 GHz for a pump wavelength of 1550 nm at room temperature. Since BS requires the conservation of energy and momentum the interaction takes place in a very narrow bandwidth. Again this depends on different parameters such as the bandwidth of the pump wave, environmental conditions and the waveguide characteristics. For our SSMF we measured a FWHM bandwidth of only 23 MHz at room temperature and a pump wavelength of 1550 nm.

Experiment: The principal setup of the wavelength measurement is shown in Fig. 1. From one side the unknown probe signal propagates through the fibre, from the other side the wave of a tunable laser source (pump) is injected into the same fibre via the port 2 \rightarrow 1 of an optical circulator. All signals at the output of the fibre propagate via the port 1 \rightarrow 3 to a *pin* photodiode. The wavelength, or frequency of the tunable laser can be controlled by a computer. In principle every tunable laser can be used. For our experimental setup we tuned the frequency of a narrowband fibre laser (≈ 1 kHz) by an amplitude modulation of an external Mach-Zehnder modulator (MZM), as shown in the right inset of Fig. 1. The bias current of the MZM was adjusted in a manner that the carrier was suppressed and only the

upper and lower sidebands are visible in the output spectrum. The lower sideband serves as the pump wave for the BS which produces a gain for the counter-propagating wave in the fibre, as shown in the upper left inset of Fig. 1. If the difference frequency between pump and probe does not correspond to the Brillouin shift in the fibre, the output signal of the photodiode (PD) is proportional to the probe wave power attenuated due to the fibre and to the insertion losses in the circulator (over all around 14 dB in our case).

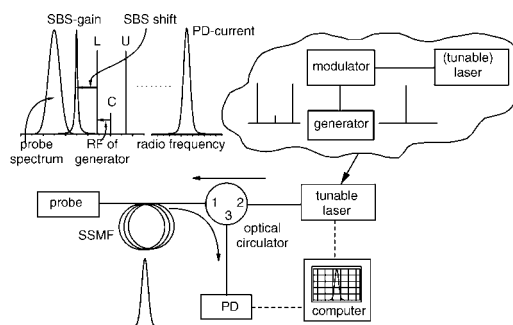


Fig. 1 Principle setup for wavelength measurement with Brillouin scattering in optical fibre

Right inset: Possible tunable laser source (SSMF standard singlemode fibre, PD photodiode)

Upper left inset: Arrangement of different spectra of sample, pump source and fibre Brillouin gain in optical frequency domain (L: lower sideband; U: upper sideband; C: optical carrier)

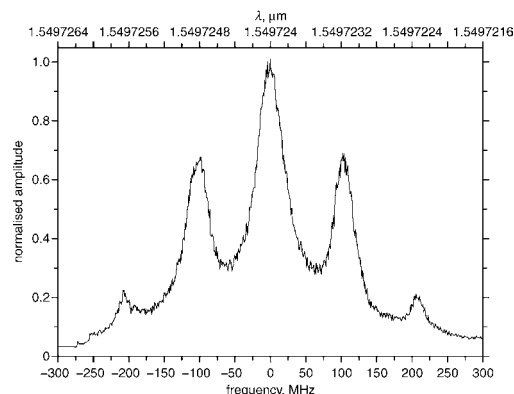


Fig. 2 Normalised amplitude of PD current depending on frequency of electrical generator, which was converted to absolute wavelength

Zero point of frequency set to centre of spectrum. Transfer function of our generator and MZM was mathematically included in spectrum

On the other hand, if the frequency difference between both waves covers at least a part of the probe spectrum this part will be amplified owing to the Brillouin interaction with the pump. Hence, the PD current begins to rise. If the frequency of the generator in Fig. 1 is increased, the BS gain induced by the lower sideband moves through the probe spectrum. Because of this, the PD current is increased until the maximum of the spectrum corresponds to the maximum of the gain. If the generator frequency is increased further the PD current begins to fall. Therefore the PD current dependence on the frequency of the generator is the convolution between the shape of the BS gain and the spectrum of the probe, as shown on the right side of the inset. If the power transfer from pump to probe is lower than the attenuation the probe wave will undergo in the fibre, the signal-to-noise ratio is too low. However, if the pump power exceeds the threshold of stimulated BS, not only the probe wave is amplified but a large amount of the pump power is scattered back. This corresponds to a pump power range between 1 and 7 mW for our experimental setup (SSMF effective length 18 km, polarisation averaged Brillouin gain $g_B \approx 1.2 \times 10^{-11}$ m/W, $A_{eff} = 80 \mu\text{m}^2$). However, we measured an increase of the Brillouin bandwidth, and therefore a decrease of the resolution, with increasing pump power. This is possibly a result of the pump depletion in the saturated regime. Because of this, we chose a pump power of around 2 mW.

For a proof of concept we externally modulated a DFB laser with a phase modulator driven by a 100 MHz signal and measured the spectrum with our setup. The result is shown in Fig. 2. The equally

spaced sidebands can be clearly distinguished in the laser spectrum. Fig. 3 shows a comparison between our measurement technique and the result obtained by an optical spectrum analyser. As can be seen, the real bandwidth of the signal is much lower than that shown by the spectrum analyser. Furthermore, as expected, the spectrum obtained by the analyser shows no fine structure of the signal shape.

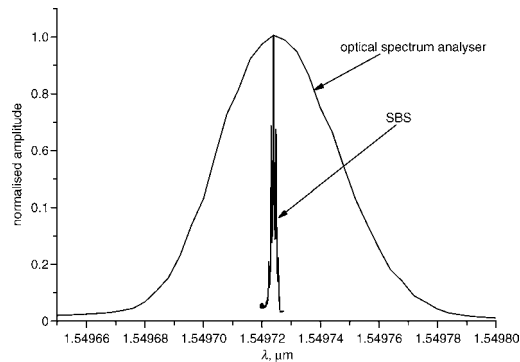


Fig. 3 Comparison between spectrum measured with optical spectrum analyser (resolution 0.1 nm) and spectrum obtained with our method

Discussion: The absolute optical frequency, respectively wavelength, of the measured spectrum is the frequency of the pump minus the BS shift in the fibre. On the one hand, this means that the accuracy of the measurement depends on the knowledge of the actual wavelength of the tunable laser. On the other hand, the BS shift depends on the temperature and the pump wavelength. These dependencies have to be known for the used equipment and the measured values have to be corrected for precise results. For our fibre we measured the frequency shift as well as the shape and bandwidth of Brillouin scattering with a similar setup as that shown in Fig. 1. We removed the probe laser and connected the fibre input and output with the tunable laser. The modulator was built in one arm of the resulting loop and the circulator in the other. In this case the unmodulated wave amplifies the counter-propagating lower sideband if the modulator frequency corresponds to the Brillouin frequency shift. Because our laser has a low line width these measurements are very accurate.

The shape of the measured spectrum and the resolution depends on the Brillouin gain in the fibre. If the spectrum of the probe is much broader than the gain, the measured spectrum follows the spectrum of the probe. If it is much smaller, the result corresponds to the spectrum

of the Brillouin gain. Thus, the resolution for our setup is around 23 MHz, which corresponds to a wavelength resolution of around 184 fm at 1550 nm. Because the shape of the Brillouin gain is known, the resolution can be increased by a computational deconvolution of the measured spectrum. Another possibility for a higher resolution is given by the temperature dependence of the Brillouin bandwidth. If the surrounding temperature of our Brillouin medium is 100°C the gain bandwidth is only 73% of the bandwidth at room temperature. Special fibres such as AllWave™ and TrueWave™ have a BS bandwidth of only 11.4 and 12.4 MHz [4] which corresponds to a resolution of 91.4 and 99.4 fm, respectively.

Conclusion: We have shown a very simple technique for the analysis of optical spectra with a resolution in the femtometre domain. With a tunable laser that performs fast wavelength sweeps, a fast and accurate measurement over its whole bandwidth is possible. With a fixed laser wavelength and an additional MZM very precise measurements in the tuning range of the MZM are offered.

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Th. Schneider (*Deutsche Telekom AG, Fachhochschule Leipzig, Gustav-Freytag-Str. 43-45, D-04277 Leipzig, Germany*)

E-mail: schneider@fh-telekom-leipzig.de

References

- 1 Parker, T.R., and Farhadiroushan, M.: 'Femtometer resolution optical wavelength meter', *IEEE Photonics Technol. Lett.*, 2001, **13**, (4), pp. 347–349
- 2 Constable, J.A., and White, I.H.: 'Laser linewidth measurement using a Mach-Zehnder interferometer and an optical amplifier', *Electron. Lett.*, 1994, **30**, (2), pp. 140–141
- 3 Lyu, G.Y., *et al.*: 'Simultaneous measurement of multichannel laser linewidths and spacing by use of stimulated Brillouin scattering in optical fiber', *Opt. Lett.*, 1998, **23**, (11), pp. 873–875
- 4 Yeniy, A., Delavaux, J.M., and Toulouse, J.: 'Spontaneous and stimulated Brillouin scattering gain spectra in optical fibers', *J. Lightwave Technol.*, 2002, **20**, (8), pp. 1425–1432