Distributed Strain and Temperature Sensing: Laser and Fiber Bragg Gratings

Simon Wörle, winter semester 2019/20

The scattering of light in optical fibers is sensitive to stretching and compression of the fibers. Therefore, they can be used to measure length changes due to both strain and temperature. They have many advantages over electrical sensors, like their non-conductivity, electrical passivity and their immunity to noise of electromagnetic radiation. Two different types of sensors have proven successful and are described in this article. The first are fiber Bragg sensors. Gratings, which reflect the strain and and temperature dependent Bragg wavelength, are inscribed at certain points. However, if a distributed strain and temperature determination is required, sensors based on Brillouin backscattering can be used. Unmodified fibers are used and the energy shift, which varies with temperature and strain changes, can be evaluated.

1 General Information on Fiber Optics
2 Fiber Bragg Grating
3 Brillouin Backscattering
   3.1 Physical Basis
   3.2 Cables
4 References

General Information on Fiber Optics

Since the 1990s optical fibers are used for structural health monitoring. They have many obvious advantages over electrical sensors like strain gauges. Optical fibers are non-conductive, electrically passive and not vulnerable to noise caused by electromagnetic radiation. Optical fibers act as waveguides. They consist of a core and a cladding made of silica (SiO2). The refraction index of the core is larger than of the cladding. Therefore, due to total internal reflection the light beam is kept inside the core. The properties of the guided laser light, like intensity, phase, polarisation and frequency are sensitive to changes in the environment.[1]

The first optical fiber based sensors were DTS (distributed temperature sensing), which uses the Raman effect and OTDR (optical time domain reflectometry) systems. Since the second half of the 1990s fiber Bragg gratings and Fabry-Perot interferometers are mainly used. The optical fibers are modified at certain positions and reflect characteristic wavelengths. However, these technologies only allow single point or quasi-distributed measurements, which means the connection and combination of many single point sensors. This could be problematic if large objects should be monitored or if the exact positions of critical points are not known. Distributed strain and temperature sensing (DSTS) provides a solution. The optical fibers are unmodified and the frequency shift of the Brillouin scattered photons is evaluated.[2]

Fiber Bragg Grating

A fiber Bragg grating is based on a single-mode optical fiber with a core which is modified over a length scale of a few millimeters or centimeters. In this area, the refraction index varies periodically, which results in the fiber Bragg grating being a dielectric mirror. The reflected wavelength \( \lambda_B \) (called Bragg wavelength) is sensitive to strain and temperature changes.[3, 4]
Figure 1: Structure and working principle of unstrained (top) and strained (bottom) fiber Bragg grating sensors[5]

Fiber Bragg gratings are manufactured from germanium doped silica fibers which are photosensitive. Therefore, ultraviolet light from an excimer laser can be used to inscribe a grating of alternating refraction index by holographic interference or phase mask. The resulting layers with a grating period act as dielectric mirrors and reflect light with the Bragg wavelength

\[ \lambda_B = 2 \cdot n_{\text{eff}} \cdot \Lambda \]

where \( n_{\text{eff}} \) is the effective refraction index of the optic fiber. The waves reflected from different parts of the grating interfere constructively. The bandwidth is typically below 1nm and the rest of the spectrum transmits the grating almost unaffectedly. Changes in temperature and strain result in a shift of the Bragg wavelength. Figure 1 shows a schematic of an unstrained and strained fiber Bragg grating together with the shift of the reflected Bragg wavelength. This can be measured immediately and is not affected by fluctuations of the source intensity. Since the Bragg wavelength depends on the grating period, it is possible to manufacture different gratings which reflect different wavelengths.[3–6]

**Brillouin Backscattering**

Distributed strain and temperature sensing by Brillouin backscattering uses optical fibers without modification. Light waves interact with acoustic phonons and the scattered light experiences an intensity and frequency shift, which is strain and temperature dependent.[7]

**Physical Basis**

Phonons are quasiparticles which represent the quantum mechanical excitation of lattice vibrations. By solving the dispersion relation one obtains three acoustic and 3r-3 optical branches, where \( r \) is the number of atoms per basis. Adjacent acoustic phonons oscillate in-phase, whereas optical phonons move out-of-phase and have a higher energy. The inelastic interaction of light waves with optical phonons is called Raman scattering and the interaction with acoustic phonons Brillouin scattering.[8] Brillouin scattering allows the simultaneous measurement of strain and temperature whereas Raman scattering only proved successful for temperature measurements[9]. The inelastic scattering can be described as the creation or destruction of phonons. The conservation of energy and momentum leads to a characteristic light spectrum. Apart from the large peak resulting from Rayleigh scattering, there are peaks with lower and higher reflected frequencies which are respectively called Stokes and anti-Stokes line.
In Figure 2 the amplitudes (in arbitrary units) are plotted against the frequency. The Rayleigh peak, which would be in the middle, is not shown. One can see that frequency shifts of the Stokes and anti-Stokes lines are sensitive to temperature and strain changes. Furthermore, the Stokes line can be used to measure the temperature while the anti-Stokes line determines the strain. This means that strain and temperature can be measured independently and simultaneously. For the backwards scattered photons the so called Brillouin shift can be described by

\[ \nu_B = \frac{2n_a}{\lambda} \]

where \( n \) is the refractive index, \( a \) the acoustic velocity and \( \lambda \) the laser wavelength. This Brillouin shift is different for different temperatures and strains. The change of the frequency shift and power are given by

\[ \Delta \nu_B = C_{ve} \cdot \Delta c + C_{VT} \cdot \Delta T \]

\[ \Delta P_B = C_{Pve} \cdot \Delta c + C_{PT} \cdot \Delta T \]

which can be represented and solved by a matrix equation. Parker et al. calculated \( C_{ve} \) and \( C_{VT} \) for a standard communications single mode fiber and wavelength \( \lambda = 1553.8 \text{ nm} \). Brillouin power and frequency are further connected by

\[ P_B = \frac{\Delta T}{\nu_B} \]

where \( A \) is a constant which can be determined by measuring frequency and power at positions in the fiber where temperature is known. After the evaluation of \( A \), measuring the power and frequency shift allows the calculation of the temperature distribution. Together with the above equations one can obtain the strain distribution along the fiber. Brillouin scattering can be spontaneous, but also stimulated. For stimulated scattering, either access to both ends or a reflection at the end of the fiber is required. A laser beam is used to induce acoustic waves into the waveguide which results in much larger acoustic frequencies.

Cables
Optical fibers consist of a silica core and a cladding. For single-mode fibers, they have diameters of 9 m and 125 m, respectively, for wavelengths of 1550 nm. Multi-mode fibers have a larger core of 50 m or 62.5 m. Single-mode fibers are used for the strain measurement whereas for the temperature measurement both single- and multi-mode waveguides are used. The actual fiber is protected by a coating. It is important that fibers which are used to measure strain are mounted under a prestressing in order to allow the detection of compressions. The used materials (coating, glue,...) should have similar strain characteristics as the measured object. In contrast, fibers for temperature measurement should be mounted without prestressing and the used materials should provide a good thermal contact.[2]

References

8. R. Gross and A. Marx, Festkörperphysik (Oldenbourg Wissenschaftsverlag, 2012)