Optical versus electrical strain gages: A comparison

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1. Introduction

Electrical strain gages (SG) are reliably used in many applications today. These strain gages were developed more than 50 years ago; today they are technically mature and available in many different versions.
For special applications - such as tests at high load cycles, use in highly explosive atmospheres or with electromagnetic interference **- optical strain gages** have recently become an interesting complement to classical strain gage technology. Using optical strain gages in these applications provides the following benefits:

- Immunity to electromagnetic interference (EMC)
- Use in highly explosive atmospheres
- No mechanical failure of the sensor material (glass) at high-level vibration loads
- Low weight of the connection leads, because fiberglass is substantially thinner than copper conductors
- Reduced wiring effort, because one measuring lead enables many sensors with different base wavelengths to be connected.

The present paper provides a comparison of the characteristics of electrical and optical strain gages and is to **provide orientation** for finding the optimal solution to different measurement problems.

Since no guideline covering the characteristics of optical strain gages exists as yet, optical strain gages from HBM have been qualified in compliance with VDI/VDE 2635 [1] **Richtlinie zur Bewertung von Dehnungsmessstreifen mit metallischem Messgitter** (guideline for evaluating strain gages with metal measuring grids).

2. Comparison of technical characteristics

a. Gage factor

The gage factor of electrical strain gages is defined as

$$\frac{\Delta R}{R} = k \cdot \varepsilon$$

R	Base resistance of the strain gage
ΔR	Resistance change at the strain impressed in the grid
k	Gage factor
ε	Strain

The resistance variation of an electrical strain gage results from two physical effects [2]:

- When a metal conductor is subject to strain, it becomes longer and thinner. Geometry considerations show that the resulting gage factor is 1.6, if Poisson's ratio for the measuring grid material is 0.3.
- The specific resistance of the measuring grid material also experiences a linear change as a function of strain. Therefore, the sensitivity of different measuring grid materials varies. The resulting gage factor is 0.4 to 0.6.

Both effects may be added. The gage factor for electrical strain gages thus is usually about 2. Very small strain gages have a smaller gage factor, because with these strain gages the effect of the change in electrical resistance resulting from strain is smaller.

Fiber Bragg sensors are based on a Bragg grating which comprises a large number of reflection points written into the fiber at periodic spacing. Impressed strains change this spacing. The wavelength of the light that is reflected by these reflection points with constructive interference thus depends on the spacing of these reflection points. Therefore, the wavelength of the reflection peak changes when strain is applied.

Two effects are crucial to the sensitivity of the measuring point [3]:

- When subject to strain, the spacing between the reflection points increases. The gage factor for this effect is exactly 1, because only the change in length of the fiber directly effects a change in spacing of the reflection points. Poisson's ratio may be neglected.
- When subject to mechanical stress, the refractive index of fibers and thus the optical distance traveled by light vary as a function of stress. The gage factor is reduced by about 0.22 so that a fiber Bragg grating has a gage factor of 0.78.

The following applies in complete analogy to the relationship for the electrical strain gage:

$$\frac{\Delta\lambda}{\lambda} = k \cdot \varepsilon$$

With

λ	Base wavelength of the fiber Bragg grating
$\Delta\lambda$	Wavelength change at the strain impressed in the grid
k	Gage factor
ε	Strain

Fiber Bragg grating sensors have thicker layers than electrical strain gages. The resulting measurement error when measuring bending strain on thin components must not be neglected; however, it can easily be corrected:

$$\varepsilon_{OF} = \frac{0.5 \cdot h}{0.5 \cdot h + d} \cdot \varepsilon_{Anz}$$

With

ε_{OF}	Strain on component surface
ε_{Anz}	Strain measured by the fiber
h	Thickness of the component
d	Distance between fiber and component surface

b. Application temperature range

The application temperature range of a strain gage is defined as the temperature range in which the sensors are able to measure and the technical characteristics of the strain gage do not change as a result of temperature influences.

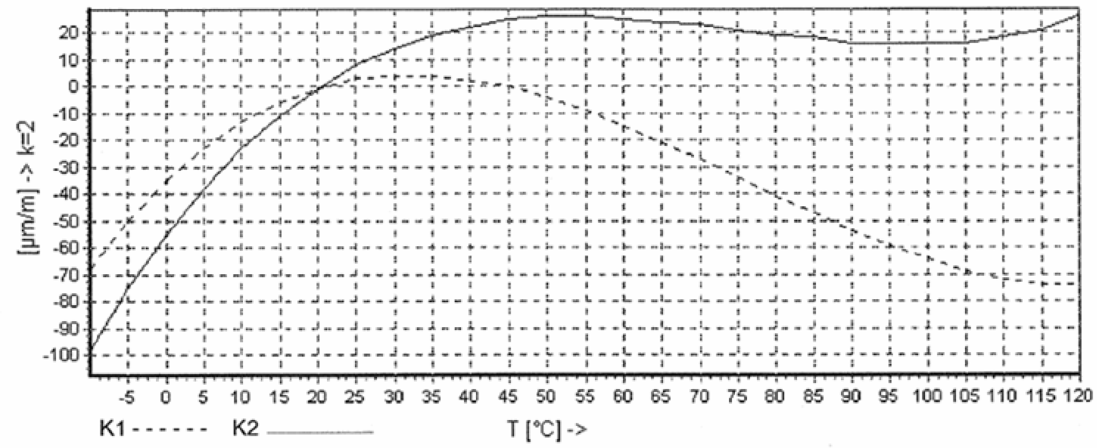
The following applies for HBM's range of products:
Electrical strain gages provide a range of -200°C to +200°C for strain gages based on constantan measuring grid foil (Y series) and -269°C to 250°C for CrNi-foil-based strain gages ("Modco", C series).

Optical strain gages from HBM can be used in the range of 0°C to 80°C (as of July 2007).

c. Temperature output signal (“apparent strain“)

With electrical strain gages, the temperature output signal can be adapted to match different materials in order to keep the error resulting from temperature variations small. The component’s thermal expansion is compensated with the curve of the specific resistance depending on the temperature.

Figure 2.c.1 shows a typical curve of the apparent strain of a strain gage matched to ferritic steel.



$$\varepsilon_S(T) = -35.4 + 2.72 \cdot T - 5.38 \cdot 10^{-2} \cdot T^2 + 2.37 \cdot 10^{-4} \cdot T^3 + 0.0333 \cdot L \cdot (T-20)\ \mu m/m \pm 0.3\ (\mu m/m)\ °C^{-1}$$

Figure 2.c.1. *Thermal output signal of a strain gage thermally matched to the test object*

At present, optical strain gages do not provide any possibility of self-compensation so that, in the case of temperature variations at the measuring point, both the component strain and the change in wavelength of the reflection peak are displayed. The change in wavelength results from the temperature-dependent variation of the refractive index. This proportion is about 8µm/m/K.

Figure 2.c.2 compares the thermal output signal of an optical strain gage installed on quartz glass, steel, and aluminum to the one of an electrical strain gage matched to the test object.

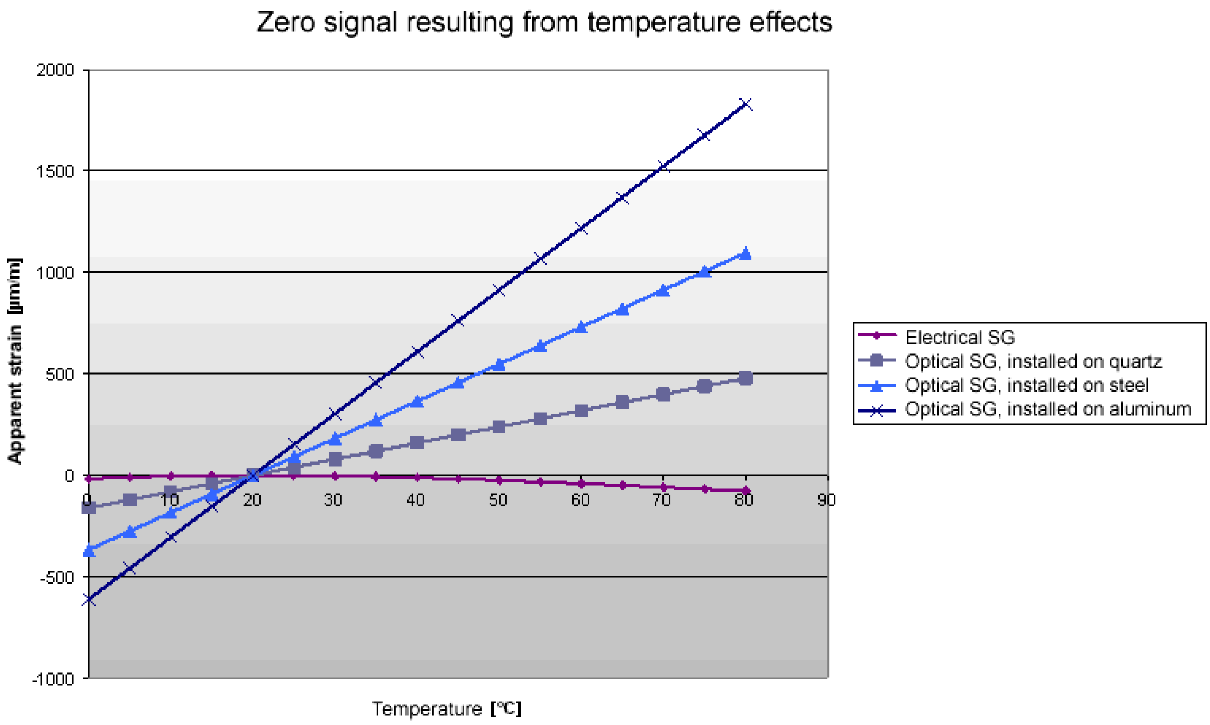


Figure 2.c.2. Comparison of the temperature output signal of optical and electrical strain gages. Optical strain gages have different installation conditions.

In general, the strong temperature dependence of the zero point of optical strain gages requires compensation, implemented either through temperature measurement or also through the use of passive temperature compensation measuring points. The reproducibility of the temperature curve of optical strain gages is very good.

d. Fatigue behavior

The resistance to long-term alternating stress of HBM's optical strain gages was tested in a constant strain field at an alternating strain of ±1000µm/m. No changes of measurement characteristics or of the reflection peak were determined after 10^7 load cycles, i. e. sensitivity and base wavelength were unchanged.

Electrical strain gages attain similar characteristics; however, they generate a non-reversible change in zero which, for the best strain gages, is about 10 µm/m.

Drawing tower fibers are used for optical strain gages from HBM. In comparison to electrical strain gages, optical strain gages tolerate substantially higher peak loads and provide a resistance to alternating loads that is higher by orders of magnitude. Earlier investigations [3] have shown that fiber Bragg gratings from the drawing tower virtually cannot be destroyed by fatigue effects at customary strains of ± 2000 µm/m.

e. Maximum elongation

The maximum elongation was determined in complete analogy to the electrical strain gages. For this purpose, the samples were subject to a bending strain monitored using a displacement transducer. With metal strain gages, the strain maximum is considered achieved when the measurement signal converted into a strain deviates from the specified strain by more than 5%.

This method cannot be used with optical strain gages, because the evaluation algorithm used determines the reflection peaks that can still be evaluated. Therefore, the maximum strain specified by HBM for its optical strain gages is the strain at which the peak is still unambiguous (main peak 4 dB above secondary peak).

Figure 2.e.1 shows a spectrum of 4 sensors with a strain level of 0. 5%. Electrical strain gages attain maximum strains of up to 10%, depending on their design (HBM's D series).

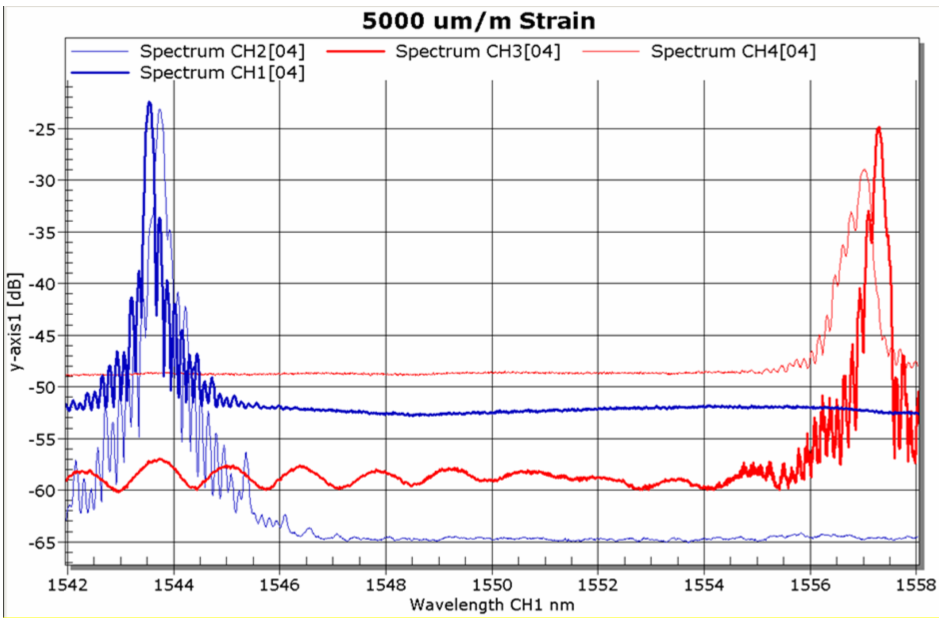


Figure 2.e.1 *Reflection peaks of the HBM patch at 5000 µm/m strain. All peaks are unambiguous.*

f. Minimum bending radius

The minimum bending radius for optical strain gages from HBM is 25 mm. When installing the patches on this radius, the measuring point will work properly.
Electrical strain gages achieve a minimum radius of 0.3 mm.

3. Summary

HBM enhances its range of products for experimental stress analysis with optical strain gages based on an innovative, attractive technology. Optical strain gages have become an attractive and powerful alternative in many fields of applications (electromagnetic stress, highly explosive atmospheres, high numbers of load cycles).

Furthermore: The patented, optical strain gages can be installed in the same way as electrical strain gages – an advantage that significantly facilitates the decision between the two technologies.

To sum up, the following factors speak in favor of opting for an optical strain gage:

1. Measurement at high numbers of load cycles: Optical strain gages allow stress tests at high numbers of load cycles (fatigue behavior) even with materials with high strains.

2. Suited even to difficult operating and ambient conditions: Optical strain gages can be used even with high electromagnetic stress or in highly explosive atmospheres.

3. Multiplexing: One fiber, many measuring points. Optical strain gages ensure reduced wiring effort. Several optical strain gages can be integrated in a single fiber of glass. The optical measurement chain thus adapts to the individual requirements of a specific application.

4. Low weight of connection leads. Multiplexing and light-weight fiberglass of optical strain gages reduce the weight of the connections. Thus the effect of the intrinsic weight of the connections on the test results is only very small (in comparison to electrical strain gages).

4. References

[1] VDI/VDE 2635 Dehnungsmessstreifen mit elektrischem Messgitter, Kenngrößen und Prüfbedingungen (Strain gages with electrical measuring grid, characteristics and test conditions)

[2] Dr. Stephan Keil. „Beanspruchungsanalyse mit Dehnungsmessstreifen" (Stress analysis using strain gages) Cuneus – Verlag 1995

[3] Michael Trutzel. „Dehnungsermittlung mit faseroptischen Bragg-Gitter-Sensoren" (Strain measurement using fiber Bragg grating sensors) Dissertation of Technical University of Berlin, Department IV. UB Stuttgart Dissertation 2001/2526, 2001

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