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Crystalline $Bi_4Ge_3O_{12}$ fibers fabricated by micro-pulling down technique for optical high voltage sensing

S. Wildermuth[a]*, K. Bohnert[a], H. Brändle[a], J.-M. Fourmigue[b], and D. Perrodin[b]

[a]*ABB Switzerland Ltd., Corporate Research, Baden-Dättwil, Switzerland*
[b]*FiberCryst, Lyon, France*

Abstract

Commonly optical high voltage sensors employ the Pockels effect in a bulk electro-optic crystal such as $Bi_4Ge_3O_{12}$ (BGO). Typically, the maximum crystal length is 100-200 mm and determined by the limits of the conventional growth technique (Czochralski). In this paper we report on the growth by a micro-pulling down technique of long single crystalline BGO fibers as an alternative to bulk crystals and their characterization for voltage sensing. The fiber thickness may range from a few 100 µm to a few mm. The parameters needed for stable growth over the entire length of the crystal were analyzed and optimized. Thin rods with a length of up to 850 mm were grown. Samples were characterized with respect to homogeneity of growth, residual birefringence (BGO is free of natural birefringence), crystal orientation, and performance under voltage.

Keywords: Voltage sensor; Electro-optic sensor; Crystal fiber

1. Introduction

Voltage and current measurement are two key functions in the control and protection of electric power grids. Traditionally, voltage is measured by means of inductive or capacitive instrument transformers. In recent years optical sensors for high voltage and current have found considerable attention as attractive alternatives. They offer improved performance (e.g. larger bandwidth), considerably smaller size and weight, environmental friendliness (no risk of oil spills) and higher safety of operation.

* Corresponding author. Tel.: +41 58 586 80 76; Fax: +41 58 586 60 04.
E-mail address: Stephan.wildermuth@ch.abb.com.

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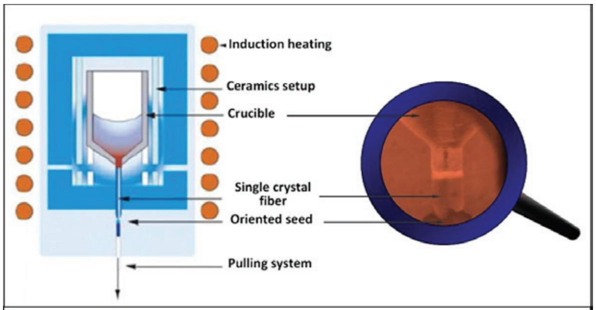
Fig. 1. Voltage sensor for 170 kV gas-insulated switchgear with a conventionally grown BGO crystal. [3].



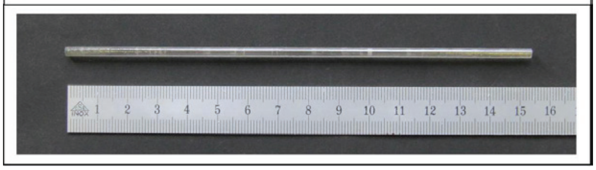


Fig. 2. Micro-pulling down technique. Top left: Scheme of the apparatus for crystal growth. Top right: Photograph of the seed crystal close to the nozzle of the crucible at the start of the pulling procedure. Bottom: BGO crystal fabricated by micro-pulling down technique.

In state-of-the-art optical high voltage sensor systems [1, 2] the full line voltage of up to several 100 kV is applied to a rather short Pockels crystal composed of $Bi_4Ge_3O_{12}$ (BGO). Typical lengths are between 100 and 200 mm (Fig. 1) and are limited by the growth method and equipment (commonly Czochralski technique). In this paper we explore the fabrication of long and thin single crystalline rods of up to 850 mm length by the micro-pulling down growth technique. Longer crystals result in smaller average electric field strength. As a result the high voltage proof packaging of the sensor becomes simpler and the lateral insulator dimensions can be substantially reduced.

2. Micro-pulling down technology

The micro-pulling down method [4] has been applied to the growth of a variety of crystals and crystalline fibers, e.g. of sapphire fibers [5] or fibers for laser applications such as Nd-doped $Y_3Al_5O_{12}$ (YAG) fibers [6]. With this technique a crystalline fiber is grown through a capillary die into the downward direction, as shown in Fig. 2.

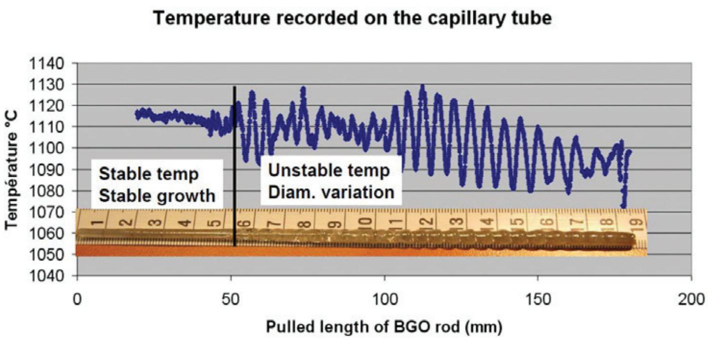


Fig. 3. Temperature measured at the capillary tube during the crystal growth process. The regime of stable temperature (left) results in a homogeneous crystal diameter, whereas fluctuations in the tube temperature cause significant thickness variations (right).

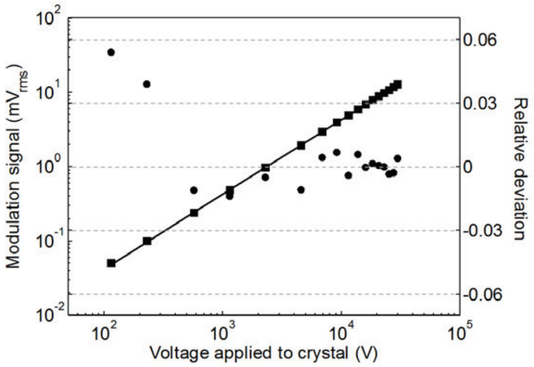


Fig. 4. Electro-optic response from a 150 mm long BGO crystal grown by the micro-pulling down technique (squares). The dots indicate the relative deviations from a linear fit.

In case of BGO the raw materials are melted in a platinum crucible at ~1050 °C by radio frequency heating. The molten material is allowed to pass through the capillary (a simple circular hole or a more complex shape at the bottom of the crucible). An appropriately oriented seed in contact with the first drop out of the crucible defines the orientation of the crystal axes.

During growth the seed crystal is slowly pulled downward at a controlled speed. The growth process is monitored by means of a CCD camera. A pyrometer monitors the capillary temperature. Furthermore, an after-heater consisting of a platinum tube reduces the thermal gradients and at the same time serves to anneal the crystalline fiber in order to reduce build-in crystal stress.

3. Results and discussion

We investigated the growth parameters needed for stable growth over the entire length of the crystal. In particular, it was found that for BGO it is rather crucial that the temperature at the crystallization zone is maintained within a narrow window (of about 10°C) in order to obtain a homogenous fiber diameter along the entire length of the crystalline fiber (Fig. 3). Fibers with lengths of up to 850 mm were grown.

A fiber section with a length of about 150 mm and a diameter of 3 mm was investigated in more detail. The sample was of good optical quality with little residual birefringence as a result of the growth process. It should be noted that BGO has a cubic crystal structure, T_d (43m), and is free of natural birefringence. The electro-optic phase shift between two orthogonal light waves (Pockels effect) increased linearly up to the maximum applied voltage of 30 kV (Fig. 4).

Crystals of class 43m enable to measure exclusively the electric field component longitudinal to the optical path if the (100)-direction is aligned in this direction [7]. The electro-optic phase shift is therefore proportional to the line integral of the field over the length of the crystal. In high voltage applications this is important to avoid cross-talk from neighboring phases. To assess the precision of the orientation of the crystallographic axes, the angle α between the long axis of the crystal rod and a homogeneous electric field has been varied (Fig. 5). For a well-oriented conventionally grown reference crystal the electro-optic phase shift at a given voltage varies in proportion to the absolute value of the cosine of α as shown in Fig. 5 (left). The investigated fiber sample exhibited an offset in the signal minimum of 19.6° (Fig. 5 (right)), indicating a corresponding misalignment of the (100)-direction. This was in good agreement with data from x-ray diffraction, indicating a misalignment of 20±4°, probably caused by an initial misalignment of the seed crystal.

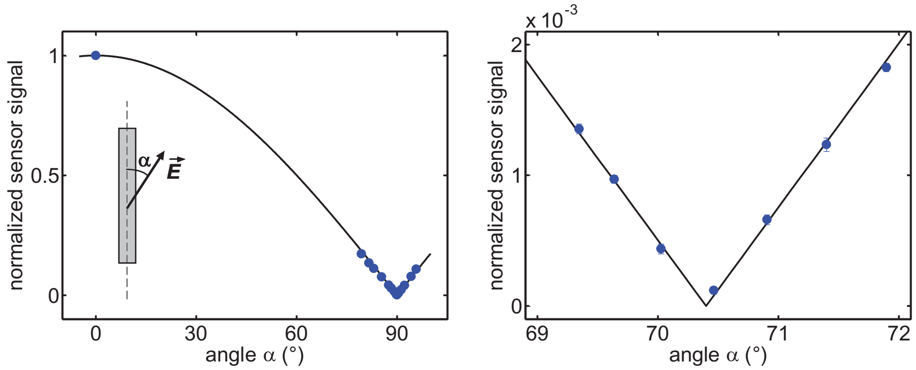


Fig. 5. Sensor signal (electro-optic phase shift) as a function of the electric field direction α. Left: A properly oriented BGO crystal (longitudinal axis parallel to (100)-direction) shows no sensitivity to transverse fields. Right: The data indicate a misalignment of the crystallographic axis with respect to the longitudinal crystal axis.

4. Conclusion

We have demonstrated fabrication of long single crystalline $Bi_4Ge_3O_{12}$ fibers for high voltage sensing by the micro-pulling down technique. Better control of the axes orientation and improvement of the surface quality is still needed to fabricate long optical fibers of high aspect ratio. A double crucible configuration may allow growing of crystalline fibers with a core / cladding structure for guided wave propagation by adding suitable dopants to the raw materials.

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