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Thermal Management of Heat Resistant FBG Sensing for High Temperature Industrial Plants

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ABSTRACT

Fiber Bragg Gratings (FBG) were fabricated by use of point by point method using precisely focused picosecond laser pulses, The FBGs can be the best candidate for strain gauge for high temperature industrial plants. For the best use of heat resistant characteristic, we demonstrated to embed the FBG sensors in metal mold to an elbow in the sodium loop. Metal adhesive is made of fine silver particles. This adhesive is applicable at very high temperature, having a high thermal conductivity and being activated in strength at 200℃. A sodium loop was constructed to develop maintenance technologies for liquid sodium handling. The main tank was filled with liquid sodium of 6 ton. Sodium was circulated with temperature of ~500℃, the flow speed of 5 m/s. In daily operation, the FBGs successfully detect periodic distortion at the elbow due to the thermal expansion. During emergency cooling, a sudden shrinking of the loop was recorded. We propose to apply FBGs to an advanced remote monitoring system for high temperature industrial plants.

KEYWORDS

fiber Bragg grating, laser processing, sodium, pipeline, thermal management, structural integrity, heat resistant, high temperature, industrial plants, monitoring, remote sensing

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1. Introduction

The development of heat resistant strain sensors was started in JAEA on March 2007 when the Noto-Peninsula earthquake occurred. This earthquake triggered slope failures [1]. We are now aiming at the structural integrity monitoring for high temperature piping system. The useful sensor element is Fiber Bragg Grating (FBG) to measure high temperature and strain. Typically, commercially available FBG sensors are produced by projecting the ultraviolet interference modulation to a single mode fiber. Index modulation at an optical fiber core is a key-issue.

One of the problems of UV-induced FBG is that operation at high temperature causes the degradation of the index modulation. Therefore, it was explored that heat resistant index modulation can be made by laser direct writing. In 1999, the fabrication of heat resistant fiber sensors by femtosecond laser pulse processing was proposed [2]. The Fiber Bragg Grating (FBG) sensor fabricated by direct laser processing was considered the best candidate for strain gauge for industrial high temperature plants [3]. In maintenance engineering, it was proposed that multi FBG sensors with different reflection peaks could make it possible to monitor the structural integrity of reactor cooling

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pipelines [4]. Writing FBGs directly into an optical fiber core by ultrashort laser pulses allows easy tuning of the peak wavelength of reflection.

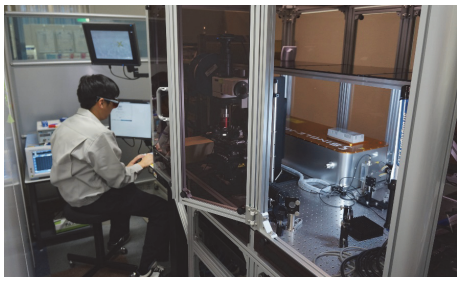
To make the best use of the heat resistant characteristic, we demonstrated several ways to embed the FBG sensor by metal mold. Silver brazing is useful method for temperatures ranging from 600 ~ 800℃. Laser cladding is other method for higher temperature application. We found that the most practical way is to use a metal adhesive containing fine silver particles. In this technique, colloidal particles were dispersed in organic solvent to form the metal mold at low temperature [5].

In this paper, we upgraded the laser processing system for FBG fabrication. Installation of FBG sensors was demonstrated in the sodium circulation loop which was newly constructed in Shiraki district of Tsuruga. This loop is a small size mock-up facility for a sodium coolant reactor. To the best of our knowledge, this is the first demonstration for monitoring temperature of sodium cooling pipeline practically by FBG sensors.

2. Experiments

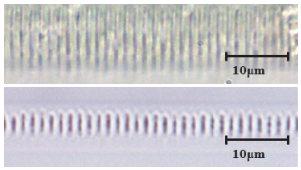
2.1. FGB sensor fabrication and sensing system

Laser processing of FBGs was reported in the previous publication[3]. Figure 1 shows the upgraded laser processing system and the improved FBG reflection performance. FBGs are written in standard Ge-doped telecom fiber by micro-focus processing with 1064nm. Figure 1(a) shows the upgraded laser processing system. Picosecond laser pulses with 100 kHz repetition can induce index modulation with a few micro-joule pulse energy. Picosecond laser pulses into fiber core are focused with a microscope objective lens. 1000 dots in the fiber core can form a single FBG. Focal depth correction correcting for chromatic aberration is important. This correction can generate a FBG without damaging the interface between the core and the clad. Dot pitch in the fiber core is chosen as the 3rd order of Bragg reflection wavelength. Controlled speed of the linear translation stage and laser pulses repetition can generate a sharp reflection peak. The improvement of the reflection spectrum is shown in Fig.1(c). Pulse energy is attenuated to the order of 5 μ J with 400 dots. Red solid line shows the FBG reflection spectrum with higher order side peaks. Blue solid line shows the improved FBG reflection spectrum. The side peaks are drastically reduced and the reflectance is improved to double intensity.

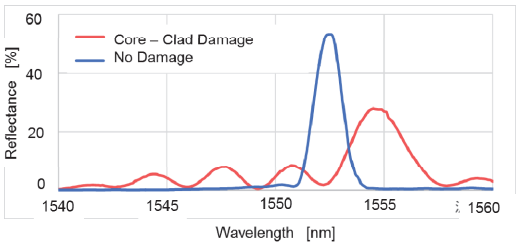


(a) Laser Processing System

A picosecond laser system and a microscope with a CCD camera were assembled. The microscopy was combined with a linear translation stage. All components were installed on an optical table.



(b) Microscopy Image of Laser Processed Fiber Core
Upper Core-Clad damage
Lower No damage



(c) FBG Reflectance Spectra

Fig. 1 Laser processing system and the improved FBG reflection performance

In order to prepare the FBG installation, 20 meters in length of two blank optical fiber were connected to each end of the FBG written optical fiber. One blank optical fiber was connected to a FBG interrogator. Thus in case of disrupted signal detection through the blank optical fiber, the other

optical fiber could be applied to the FBG interrogator. The following performance is required for a FBG interrogator; high frequency response, portability, all solid state, highly robust optics, long lifetime and high stability of light source. Low electricity consumption is important too. Battery operation should be available in a station blackout emergency. In our experiments, the wavelength was ranging from 1528 to 1568 nm. Scanning frequency was 2.5 kHz. Wavelength stability was less than 5 $\times 10^{-12}$ m (5 pm) over operation condition.

2.2. Sodium Circulation Loop

Sodium has been used as liquid metal coolant to maintain the neutrons fast energy spectrum in collisions. It is indispensable to the primary cooling system of fast neutron reactors. At present time, sodium is used not only in the primary cooling system but also in the secondary cooling system. Radioactive sodium flows through reactor core, primary cooling loop and intermediate heat exchanger. Non-radioactive sodium flows through intermediate heat exchanger, secondary cooling loop and boiling heat exchanger. To develop the maintenance technologies for reactor vessel and cooling pipeline, a special research facility for sodium engineering was designed and constructed.

Figure 2 shows the outline of the sodium circulation loop. Sodium is heated up to 550 ℃ by electric heating. The maximum flow velocity in a 3 inch diameter pipe is 5 m/s. The flow is driven by an electro-magnetic pump. The sodium gross weight of 5.5 tons was filled in the circulation in 2015. Temperature of the loop line should be maintained higher than 200 ℃ in order to prevent local sodium solidification. The loop has two tanks and one circulation section for various experiments. An oblong tank and a lengthwise tank are connected to a circulation loop. The shallow oblong tank measures 1.5m in diameter outside with 2.5m in height. The deep lengthwise tank has a 0.8m outside diameter and 7m in height. Using these tanks, development of robotic arms, eddy current testing and ultrasonic echo detection is under planning.

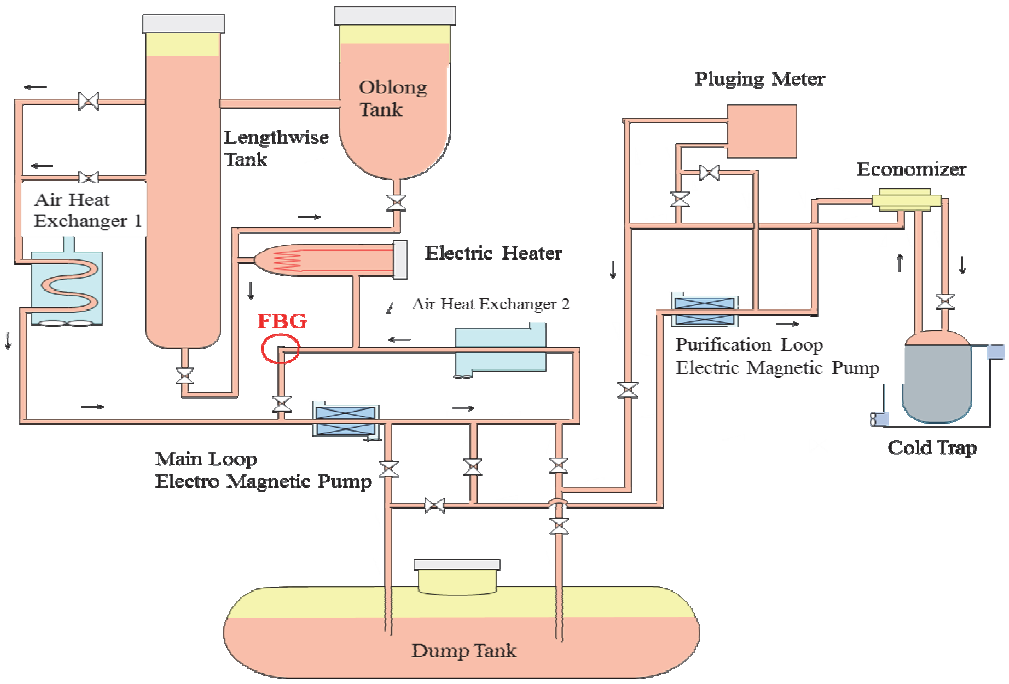
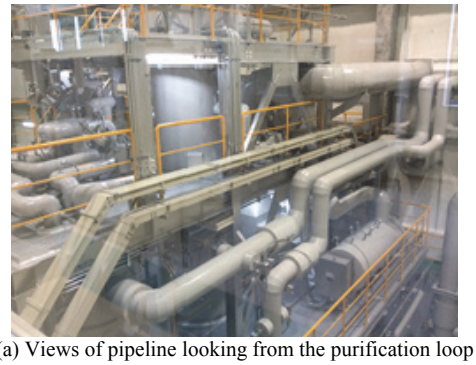


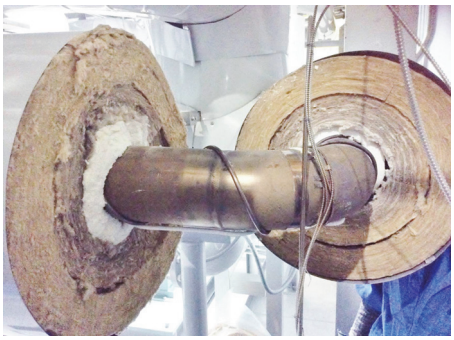
Fig. 2 Outline of Sodium Circulation Loop

The position of FBG sensors is shown in Fig.2 by a red circle. In this setup, liquid sodium flows from the deep lengthwise tank through the air heat exchanger-1 and into the main loop electric magnetic pump. Then liquid sodium can be directed to the air heat exchanger-2 into the electric heater and back in the deep lengthwise tank. Thermo-couples and electromagnetic flowmeters are used as standard sensors for daily operation. All signals from these sensors are monitored in the operation room. Figure 3 shows the sodium circulation facility and SUS pipeline wrapped with heat insulator.

Figure 3 (a) shows a picture of the pipeline looking from the purification loop. The pipeline is wrapped with rock-wool heat insulator and steel covers. Figure 3(b) shows the elbow section of the SUS pipeline when a steel cover and a heat insulator are taken off. They are renewed to be detachable.



(a) Views of pipeline looking from the purification loop



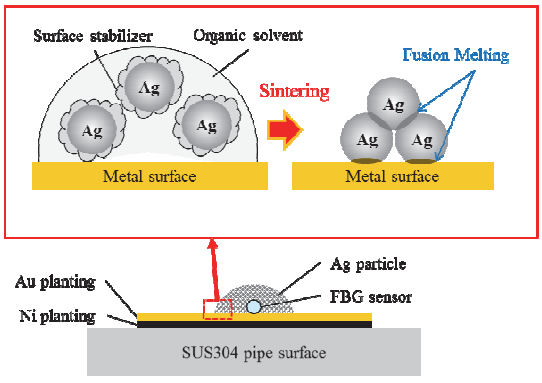
(b) Cross sectional view of the elbow of SUS pipeline wrapped with heat insulator

Fig. 3 Sodium circulation loop and SUS pipeline wrapped with heat insulator

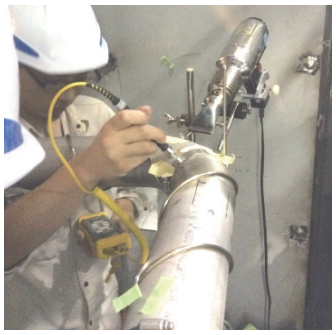
2.3 Installation of FBG sensors

An optical fiber clad is coated by an UV hardened layer to keep the fiber strong enough. After processing FBG in the optical fiber core, we removed the UV hardened coating layer completely. Metal surface of a SUS pipeline was cleaned and coated with a thin gold layer by electro plating. For the successful installation, the following procedures are carried out.

Figure 4(a) shows the mechanism of sintering for bonding FBG sensors on a SUS plate. Colloidal silver is a suspension of the element in a solution of organic solvent(1-Methoxt-2-propanol). The base colloidal solution contains average size particles ranging from 400 nm to 1000 nm. Cure for sintering is started by 10 minutes preheating during which the solution was transformed to non-flowing mold. Keeping 200 ℃ for 1 hour was required to finish sintering. Colloidal silver nano-size particles were connected at the interface and then a network structure was completed.



(a) Mechanism of sintering colloidal silver adhesive for FBG sensors. Electro plating with Ni and Au is applied on the SUS pipe surface.



(b) Sintering with monitoring the temperature of the elbow. A hot blow torch heats the mold of FBG covered with colloidal silver adhesive.

Fig. 4 Colloidal silver sintering process for bonding FBG sensors on a SUS plate

Figure 4(b) shows the sintering procedure with monitoring of the temperature of the elbow to install the FBG sensors. A blow torch was used to heat the surface of an elbow all around. A thermocouple was used to monitor the elbow's surface temperature maintained in 200℃ for one hour. It was easy to check the metallization by watching the color change. Original color of the mold was wet dark gray. After metallization, the color turned to powder-snow white. Sintered fine silver particles were tightly connected each other.

A summary of the installation procedure is given below:

Step 1 Cleaning up the metal surface by wiping. Dust, oil and rust should be removed. Mechanical grinding and polishing are effective.
Step 2 Applying nickel plating as an undercoat on the metal surface. Coating gold plating over on the nickel plating.
Step 3 Removal a UV hardened coat of a fiber clad completely by a handy peeler.
Step 4 Cleaning the bare clad fiber gently by a cotton paper impregnated with ethyl alcohol.
Step 5 Contacting the bare clad fiber to the metal surface
Step 6 Spreading metal adhesive over the bare clad fiber to form a mold.
Step 7 Heating the mold at proper temperature and keep it until metallization is observed.

Figure 4(b) shows the heating process (Step 7) on the elbow of the sodium circulation loop. A spiral sheath heater was pre-installed around the pipeline. A hot blow torch locally heated the mold of FBG which was covered with colloidal silver adhesive. During heating process, visual inspection and temperature monitoring were carried out. The optical fiber was protected by a SUS bellows sheath and routed to the operation room through the cable rack of the facility.

3. Results and Discussion

3.1 Experimental results by FBG sensing

Figure 5 shows an experimental result of the reflection peak shift of three FBG sensors on the elbow. Ch1 (blue plots) indicates the data of the FBG sensor at the lower side of the elbow. Ch2 (red plots) indicates the data on the upper side. Ch3 (green plots) indicates the data of an FBG which was not bonded mechanically but touched thermally on the surface of the elbow. Thus, Ch1 and Ch2 were able to detect thermal expansion/distortion of the elbow. On the other hand, Ch3 detects only effects of temperature by heat conduction. Solid line (orange) shows temperature measured by a thermo-couple.

Heating by the spiral sheath heater started at 11:00. Peak shift caused by temperature change is 10×10^{-12} m/℃ for FBG. Temporal change of Ch3 agreed well with that of thermo-couple. At 13:10, the temperature of the elbow reached 200 ℃ and then began to oscillate with a stable periodic change of ~20 ℃, showing that the loop was maintained under PID control at 14:00 and later.

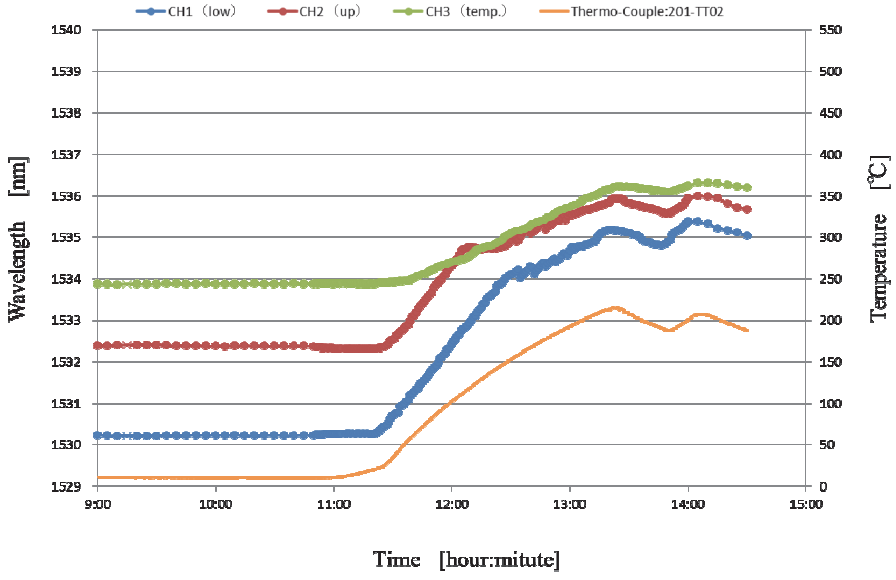


Fig. 5 Reflection peak shift of FBG sensors in start-up heating of the sodium circulation loop..

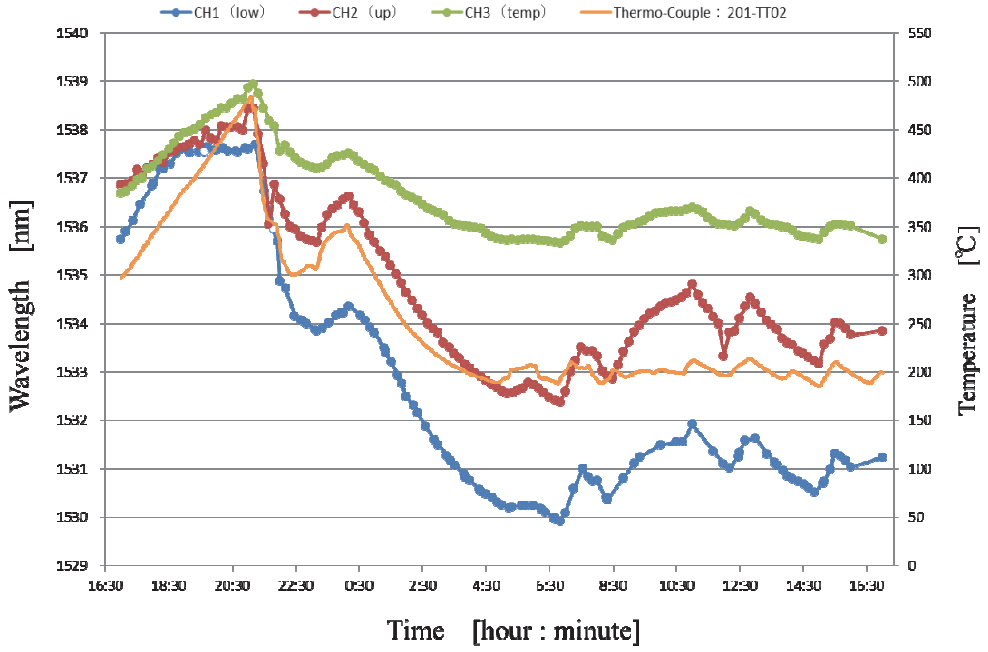


Fig. 6 Reflection Peak shift of FBG sensors in emergency shut-down of the sodium circulation loop.

Temperature of the sodium circulation pipe was maintained 200 ℃. Sodium was charged into the pipeline from the dump tank and then the electric heater was turned on to heat up the sodium toward 500 ℃. Figure 6 shows the final stage of heating process stating from 300 ℃ of the sodium circulation loop. During heating process, we faced the emergency when the safety interlock was activated. Heating current was immediately shutdown at 21:10. This was caused by malfunction of a sodium electro-magnetic flow rate meter. After rapid cooling, the temperature went back to almost 200 ℃ at 5:00. Ch3 shows the peak shift which is almost equivalent to temperature drop measured by the thermo-couple. Both Ch1 and Ch2 show larger peak shift than CH3. Especially CH1 shows 4 nm extra peak shift which was caused by thermal shrinking.

3.2 Discussion for blue shifts of FBG peak wavelength

The experimental results show a possible application for monitoring high temperature industrial pipelines. It is the inspection of thermal annealing of the distortion which was induced by construction welding. Every pipeline may have more or less distortions initially by butt-welding. Especially, in the case of a closed pipeline, welding which completes the loop is sure to generate internal stress. Table 1 shows the summary of reflection peak change of FBG sensors. Stage 1 shows the initial values of reflection peak wavelength of each FBG sensor. Peak shift caused by strain is 1.2×10^{-12} m/μ strain (1.2 pm/μ strain) for FBG. Stage 3 shows the maximum peak shift at the maximum temperature. Ch1 indicated the peak shift of +7.5 nm which was 2.5 nm larger than that of Ch3. And Ch2 indicated the peak shift of +6.3 nm which was 1.3 nm larger than that of Ch3. These excess peak shifts Ch1 and Ch2 were surely caused by thermal expansion of the pipeline. After the emergency shut down of the stage 3, the pipeline was controlled at 200℃ at the stage 4 without any damage. The 6th column of Table 1 shows the difference of the FBG peak between stage 2 and stage 4. Both Ch1 and Ch2 show the blue shift of the FBG peak. Especially Ch1 indicates larger blue shift of 4.0 nm. The reason why they showed such blue shifts could be caused by the relaxation of initially induced distortion, in other words, annealing the butt-welded pipelines. The peak shift of 4.0 nm is equivalent to ~3300 μ strain. Thus, it means that very small but measurable shape change occurred in the elbow. Only heat resistant FBG strain sensors installed under heat insulators can detect such small changes.

Table 1 FBG peak shift

	Stage 1 Room Temperature	Stage 2 Pre-Heating (～200℃)	Stage 3 Max-Heating	Stage 4 Rapid Cooling (~200℃)	Difference Stage 2 - Stage 4
Ch1 (nm)	1530.2	1535.1	1537.7	1531.1	4.0
Ch2 (nm)	1532.3	1535.8	1538.6	1534.0	1.8
Ch3 (nm)	1533.9	1536.2	1538.9	1536.0	0.2
T. C. (℃)	13.8	200.0	482.0	200.0	0

3.3 Future deployment of FBG sensing for high temperature piping systems

Indeed the sodium circulation loop was constructed for the development of thermal management of fast breeder reactors. To date, however, the framework of the development should be reconsidered. Only if the inflexibility on the current development plans of FBR has been solved, we could reconsider various possibilities. The most important viewpoint is to renew the concept of steam generators, which was mentioned in discussions of the previous paper [6]. The key issue is to use inert, heat proof and stable liquid in secondary circulation loop of FBR as heat transfer fluid instead of liquid sodium. Silicon based machine oil can be utilized. However, in high temperature condition over 500 ℃, molten salt could be the best candidate.

In solar energy utilizations, the advanced system is designed with combination of concentrated solar power generation; smart grid network and high-voltage DC power lines [7]. The DESERTEC Concept offers worldwide sufficient clean power to mankind, which must be supported by global international collaborations. In order to utilize solar power for 24 hours, molten salt is charged in the pipeline and storage tanks. A tower-type heat receiver can absorb the reflected solar energy from computer controlled mirrors. In the other case, a huge cascade of tubular receivers can absorb the solar power by cylinder-like reflectors. Operational temperature of molten salt was designed to be around 350 ~ 600 ℃ during daytime operation. The molten salt, a mixture of sodium nitrate and potassium nitrate, is environmentally friendly and can be utilized as fertilizer when the plant is eventually decommissioned. The molten salt is stored at 566 ℃ in a storage tank which is located underground.

4. Conclusion

The heat resistant FBG sensors were fabricated by femtosecond laser processing. A newly constructed sodium circulation loop was used for the installation demonstration. The FBG sensor was successfully installed on an elbow of the pipeline by metal adhesive. In the operation room, remote sensing was carried out to detect strain and deformation of the pipeline. In the emergency shutdown caused by malfunction of a sodium electro-magnetic flow rate meter, the heat resistant FBG sensors detected the sudden shrinking and annealing phenomena of the sodium circulation loop.

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