Plasma chemistry attacks new tasks for fiber optics and optoelectronics

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Optical fibers and Bragg gratings

Modern optical fibers for telecommunication are made of silica based glass. Core plays a key role in the construction of the optical fiber. It is a thin glassy region 6-8 microns in diameter, situated in the middle of the fiber. Glass in the core has an increased index of refraction as compared to the glass in the periphery. Due to this feature electromagnetic field of light is concentrated in the vicinity of the core. Thus it is the core that serves for carrying light in the body of the fiber preventing it from negative interaction with surrounding environment.

Depending on core glass composition, fiber can acquire a lot of additional useful properties. For example refractive index of some glasses in the core can be changed by a side exposure to UV laser light. Such fibers are called photosensitive. Photosensitivity makes it possible to imprint the so called Bragg gratings in them. In-fiber Bragg grating is a piece of optical fiber 0.3-3 cm long where the core refractive index $\boldsymbol{n}$ is modulated in the lengthwise direction with a spatial period $\boldsymbol{L}$=300-600 nm. Bragg grating is formed when a piece of photosensitive fiber is placed in the plane of interference pattern created on the basis of laser radiation in the wavelength interval of 190-270 nm. As for the light, guided by the fiber this structure represents a spectral selective mirror with the maximum reflection at a λ_B wavelength satisfying the Bragg condition $\lambda_B=2*L*n$.

Ordinary fiber optical measuring equipment allows to determine the Bragg wavelength spectral position with a high accuracy thereby letting one follow the changes in $\boldsymbol{L}$ and $\boldsymbol{n}$ values caused by external exposures. This is the principle to run the fabrication of optical fiber sensors of various physical parameters. Among the irrefutable advantages of such optical fiber sensors are small size, versatility, remote monitoring of the object under study (up to several kilometers) without characteristics loss, and chemical stability. An all-optical readout system without using electric elements and circuits makes them safe in operation within explosive environment and absolutely insensitive to electromagnetic fields. All these advantages provide for the application of these optical fiber sensors instead of standard ones by gradually replacing them as wall as in the places inaccessible for other sensors.

Application of Bragg grating sensors at high temperatures

The weak point of optical fiber sensors based on conventional Bragg gratings is their comparatively low temperature resistance. Normally such a sensor can't even stand short-term heating up to 400-500 °C because of irreversible degradation of the Bragg grating, though the silica fiber as such can operate under temperatures up to 1000 °C long term. The reason of comparatively low temperature resistance of the gratings is associated with the decay of photo-induced changes in refractive index that occur in the fiber with writing down of the grating by the UV radiation.

To enhance temperature resistance a novel type of silica fiber is applied in the course of in-fiber Bragg grating sensors fabrication. In this novel type of fiber it is nitrogen that is used to shape refractive index profile in the core instead of germanium. The use of this new hydrogen-free high purity silica in fiber optics owes to the plasma chemical synthesis technology. Hot electrons of glow discharge plasma open up a channel for participation in glass synthesis chemistry of such strongly coupled and inert molecules as N_2 by stimulating chemical transformation even at relatively low kinetic temperatures of molecules in a gas. It was later demonstrated that photo-induced Bragg gratings written by a conventional method in the nitrogen-doped silica-core fibers withstand heating to temperatures up to 1000 °C.

An important element of in-fiber sensors intended for use at high temperatures is the fiber protecting coating, without it glassy fiber is very fragile. Polymer coating usually used for fiber protection cannot operate at such high temperatures. Help has come from metal coating. It was established that a coating layer only several tens of microns in thickness made from a copper-based alloy serves as an excellent protection even under a long term exposure in air at temperatures up to 500 °C.

Enhanced temperature resistance enables one to widen the borders of the optical fiber sensor application. So the increase in operating temperatures limit up to 900 – 1000 °C makes it possible to apply such sensors in the oil and gas industry, in particular, in oil well monitoring. It can make the process of deep oil wells drilling monitoring and oil and gas production cheaper and faster. Resistance to high temperatures of these sensors opens the way for their application for expensive electric turbines and power-plant monitoring, for simple and fast diagnostics of condition and operating modes. This sensor is irreplaceable in high-power microwave set-ups and furnaces where the use of the sensors of other types is impossible because of simultaneous high frequency intense electromagnetic fields and high temperatures.

On the way to integrated optoelectronics

As well as it has occurred with semiconductor industry where discrete transistors in mass production were gradually substituted by integrated circuits, the future of optoelectronic devices is inevitably associated with size decrease and integration. An important issue of integration in optoelectronics is the miniaturization of optical quantum amplifiers which are the components intrinsic to modern fiber optics telecom systems.

Quantum optical fiber amplifiers are built up on the basis of a specialty optical fiber with the core made from glass doped by Er^{3+} ions. Such fibers are called active. Active fibers acquire ability to amplify optical signals when exciting Er^{3+} ions by pump light from a lased diode. Typical lengths of the active fibers in modern erbium-doped fiber amplifiers are about several meters and over. To shorten these lengths down to several centimeters and thus to go to integrated optical schemes with the same amplification coefficient a hundred times increase of erbium concentration in waveguide's core glass is necessary. At such high concentrations a significant portion of erbium ions in conventional fused silicate glass is gathered in a cluster because of a limited solubility of erbium oxides in silicon dioxide melt. The follow up is that gain efficiency with respect to pump power sharply goes down as there appear new relaxation channels for excited erbium ions, the channels being not connected with stimulated light emission necessary for amplification. For this reason a significant increase in pump power consumption is necessary to achieve a given gain value. This in turn causes the necessity to apply more powerful and thus more expensive and less reliable diode lasers for pumping.

To fabricate silicate glasses with simultaneously high erbium ions concentration and quantum gain efficiency it is necessary to somehow overcome the strong from the point of view of thermodynamics restriction on mutual solubility of the oxides. A solution was found in applying plasma chemistry to glass synthesis. In this technology oxide molecules are generated in the gas phase whereas glass is formed by deposition of the molecules on a relatively cold solid surface so that a possibility of erbium ions migration in glass is dumped. Absence of a liquid phase hinders clusters formation although their appearance corresponds to free energy minimum and is inevitable when glass synthesis occurs under thermodynamically equilibrium conditions.

As was shown in the experiments, non-fused erbium-doped silicate glasses synthesized by plasma chemical deposition method retain a high quantum efficiency similar to that one of active optical fibers with low Er^{3+} concentrations at erbium ions content as high as $3 \cdot 10^{20} cm^{-3}$. This technology opens a way to fabrication of erbium-doped waveguide amplifiers with active waveguide length being a few centimeters. As a result switching to lasers and amplifiers in form of optical integrated circuits becomes a topical issue.

References:

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