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Development of optical devices based on rare-earth doped fluoride fibers

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ABSTRACT

Optical devices made by using rare-earth doped fluoride fibers are now commercially available, and have been widely used, for example, as test sources to evaluate WDM components. We will review these fiber-based devices, which include ASE (Amplified Spontaneous Emission) light sources and optical fiber amplifiers in the S, C, and L bands, and fiber lasers in the near infrared region.

Keywords: Rare earth, Optical Amplifier, ASE Light Source, Fiber Laser, Fluoride Glass Fiber

1. INTRODUCTION

The rare-earth doped fluoride fiber has a couple of advantageous features over silica fibers when it is used as an active device. Due to the nature of the fluoride fiber whereby host glass is composed of heavier elements than silica fiber, resulting in lower phonon energy, higher emission efficiency than silica fiber can be expected. In fact, emissions in the 1300 nm 1400 nm and 1500 nm regions can be readily available, while emissions in the 1300 nm and 1400 nm bands from silica fibers are normally much weaker. And thus, one of the major applications of the fluoride fiber is as a broadband light source for these bands. Another interesting feature of the fluoride fiber is that the fluoride glass is a multi-component glass. Normally, there are about 10 components included in the glass, resulting in a variety of ligand fields around rare-earth elements, and hence, a broader emission spectra than silica fiber can be obtained. Thanks to this feature, fluoride fiber based amplifiers can have broad and flat gain spectrum without any gain flattening filters. Thirdly, since the fluoride fiber can transmit 2-3 μm wavelengths, a couple of fiber lasers in the near infrared region have been developed.

On the other hand, there had been concerns that these exotic fibers tend to be fragile, and also sensitive to moisture, and hence, it would be difficult to use them for commercial products. With upcoming fiber module techniques, however, where the fluoride fiber is hermetically sealed under inert atmosphere, the reliability issue has been drastically improved. In fact, these modules have passed typical heat cycling, humidity, shock, and vibration tests. Another concern was the damage caused due to high power density in the fiber and the fluoride /silica fiber interface, which has been also solved by improving the fiber quality or purity and also by eliminating the gel, which used to be used at the fiber interface.

This paper reviews these fluoride fiber based devices including ASE light sources, optical fiber amplifiers and fiber lasers.

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2. ASE LIGHT SOURCE

An ASE (Amplified Spontaneous Emission) light source is basically constructed from rare-earth doped fiber and its pumping source, which is normally an LD, as the basic structure is shown in Figure 1. An appropriate combination of the rare-earth elements and pumping wavelengths gives rise to certain emission; 1300 nm emission from Pr-doped fluoride fiber, 1400 nm from Tm-doped fiber, and the 1500 nm region from Er-doped fiber. Typical ASE spectra are shown in Figure 2. The ASE unit first started with one which emits in the 1530 nm through 1570 nm region, the so-called C-band, but as the demand for increasing the capacity of the WDM system increased, ASE light source covering 1530 nm thorough 1610 nm, the C- and L-band, (FL700x series) was then launched in 1999. Since the trend to expand the transmission window further continued, especially towards the shorter wavelength region, the S-band, the S-band ASE light source, (FL720x series) was presented in 2000. As can be seen, since there was a gap in terms of the spectrum between the FL7002 and FL7201, there had been a strong demand for ultra-broad ASE light sources covering the S-band through the L-band. In 2001, the FL7701 was launched, which has a power density of more than – 20 dBm/nm over 1440 nm through 1610 nm.

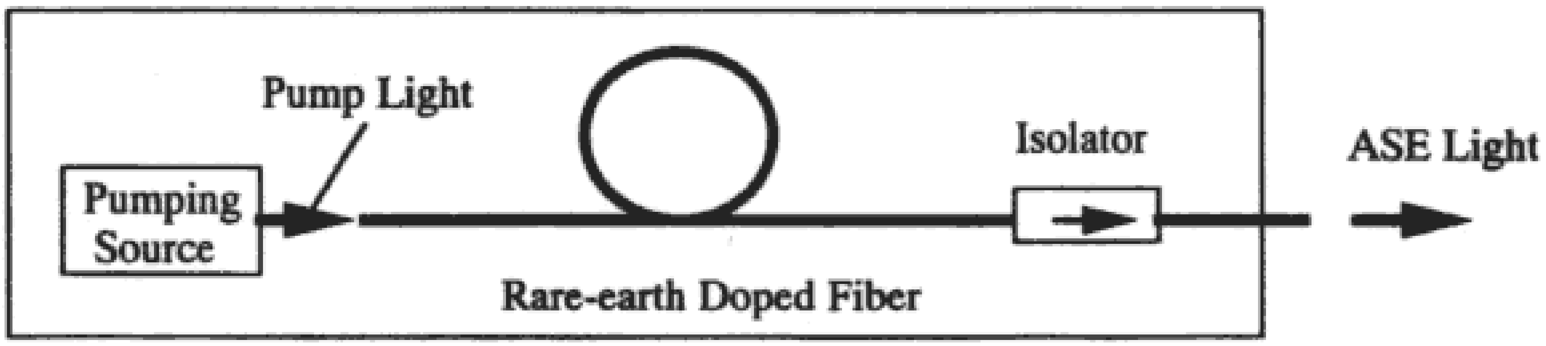

Figure 1: Schematic Diagram of ASE light source.

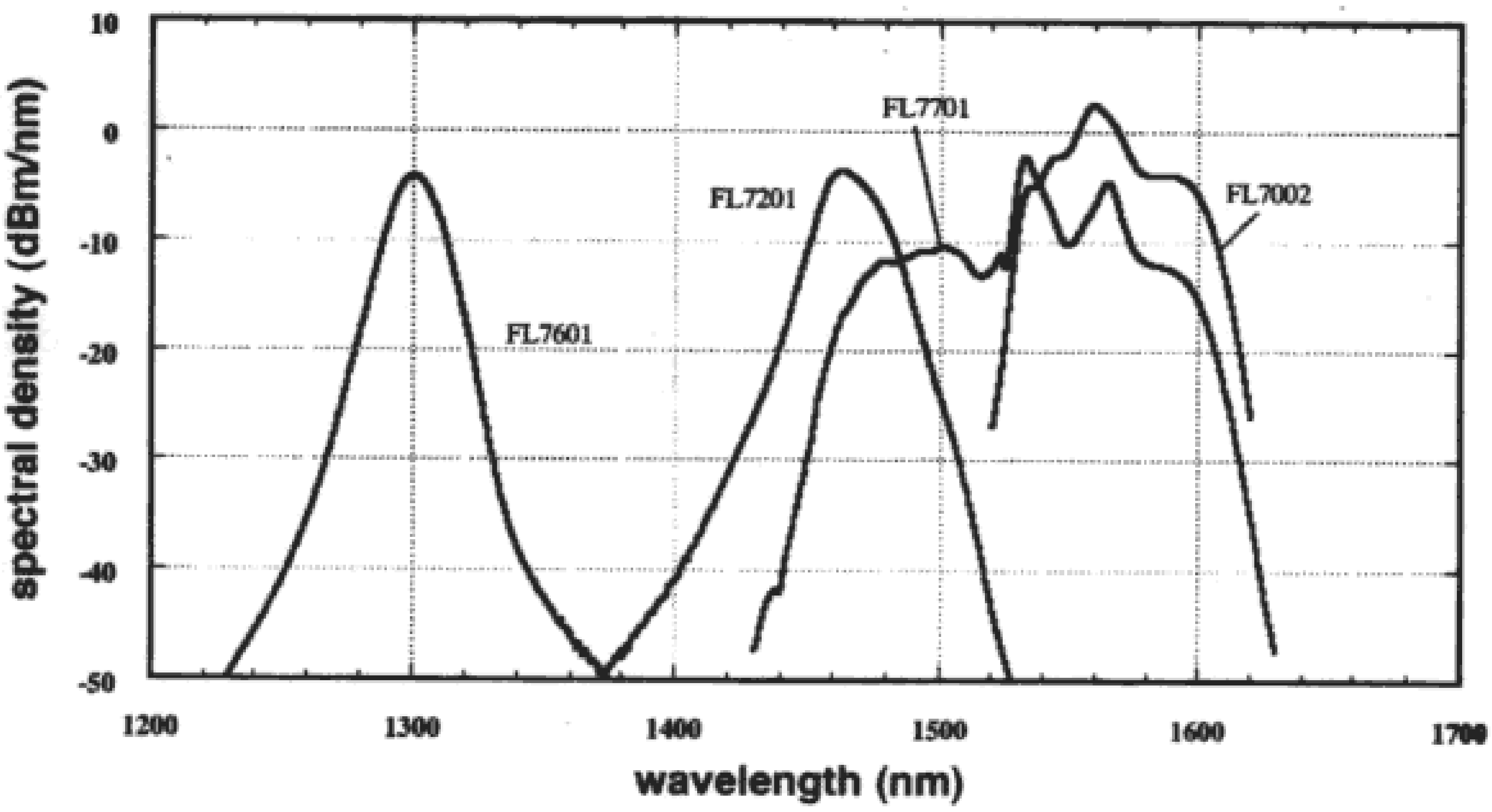

Figure 2: Output spectra of ASE light sources.

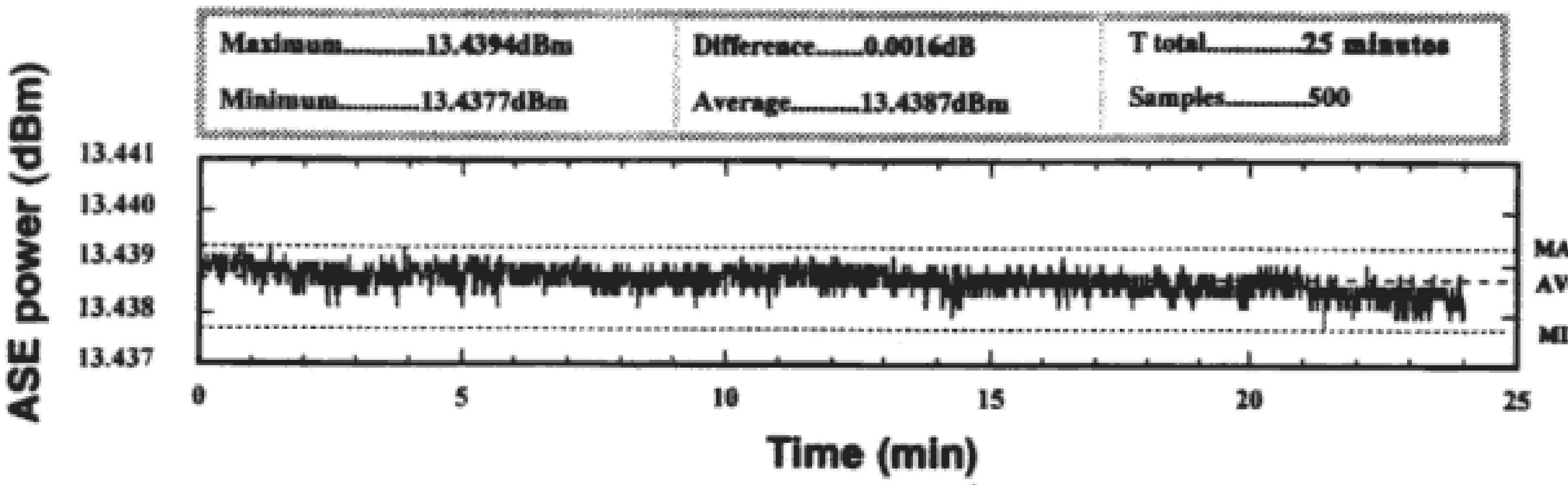

Figure 3: Power stability of ASE light source, FL7002, 25 minute time interval

Compared to other conventional light sources such as LED and LD, one of the features of the ASE light source is its broadband spectrum with high spectral power density. Typically, the total output power ranges from 1 mW through 150 mW, and the bandwidth for more than –20 dBm/nm ranges from 40 nm through 140 nm. Another feature of the ASE light source is its output power stability and spectral stability. Figure 3 shows the output power stability of the 1.5 μm ASE light source FL7002. The short-term power stability in the 0.002 dB range in a 25-minute test and the long –term power stability in the 0.01 dB range in a 48-hour test is much better than conventional light sources. In Figure 4, to simultaneously illustrate the power and wavelength stability of the 1.4 μm ASE light source, two traces are recorded 15 minutes apart. By subtracting these two plots, variation in the spectral density becomes apparent.

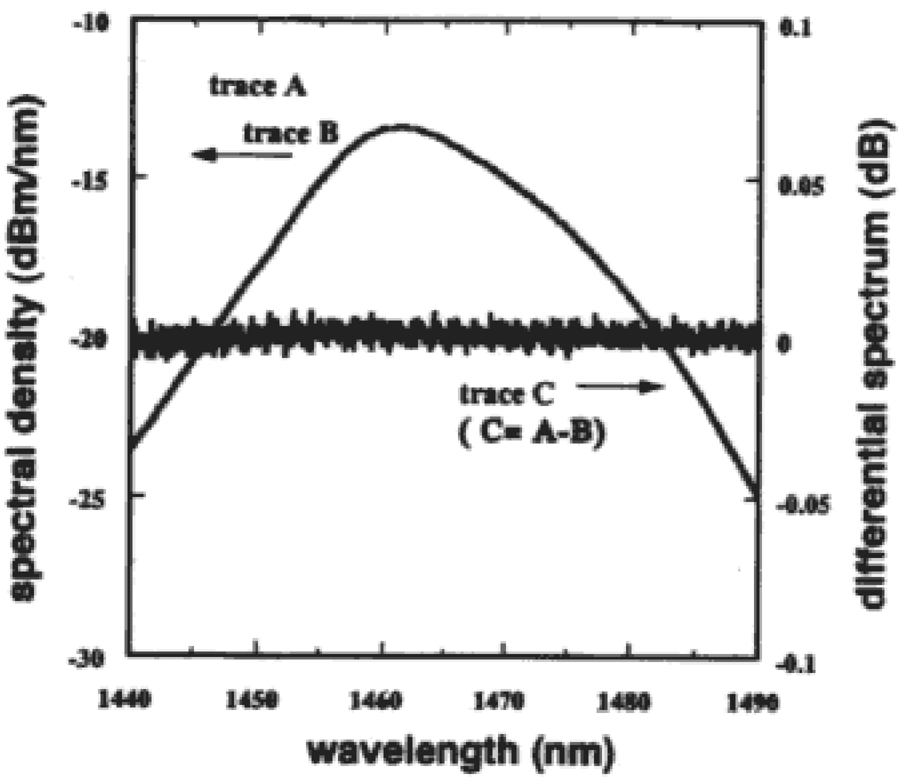

Figure 4: Differential spectrum showing power stability over a 15 minute time interval.

Because of this great power and spectral stability as well as broad bandwidth and high brightness, the ASE light sources are widely used to evaluate almost all the passive components for the WDM telecom system such as optical fiber, WDM coupler, fiber Bragg grating and optical filters. The ASE light source is commonly used as a white light test source together with an optical spectrum analyzer. This combination can evaluate the performance of the passive component with high wavelength resolution and also with a large dynamic range over broad bandwidth. Figure 5 shows examples of the measurement results for optical 1x4 beam splitter. As can be seen, there are small variations or undulations in the insertion loss, which might be overlooked if the data were taken at a discrete wavelength. As the WDM system increases in size, the number of the passive components used in the system drastically increases, and the accumulation of tiny deviation from the specified values or variation in the performance of each component could

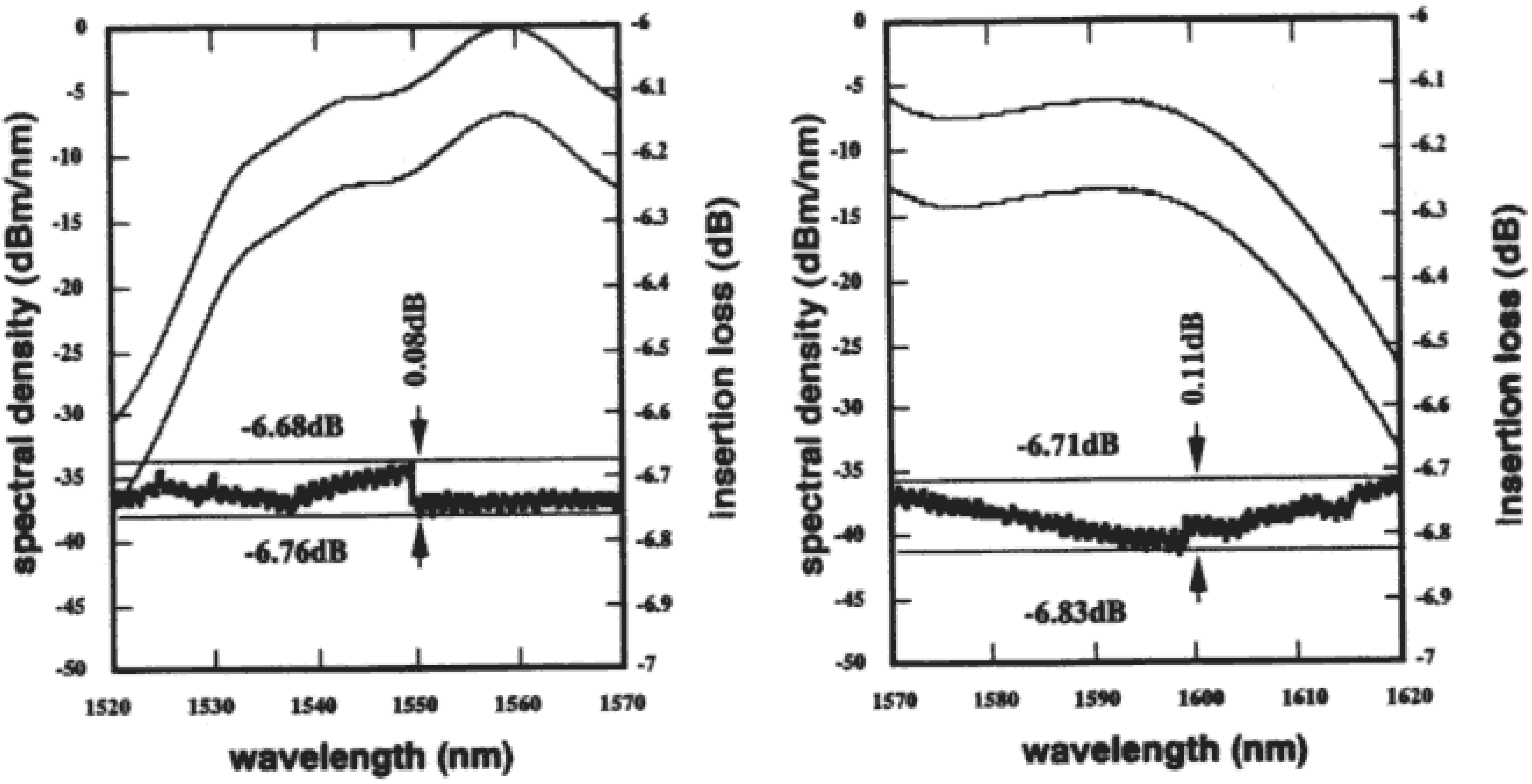

Figure 5: Measurement results of insertion loss of 1x4 beam splitter using ASE light source. Upper two traces are ASE spectra before and after inputted into the splitter, and the lower trace is the insertion loss measured by subtracting two spectra.

result in system error. In this way, the precise evaluation of passive components is very important not only in factories but also more importantly, for those companies that use these components. This broad bandwidth simplifies the measurement processes over a wide wavelength region, and also high output power density assures measurement results with a large dynamic range.

One such ASE-related product is the multi wavelength light source, the spectrum of which is shown in Figure 6. The output spectrum from the ASE light source is sliced by a series of filters into multi wavelengths. This instrument offers small optical power variation among wavelengths and extremely low ASE noise or a large dynamic range, which makes possible accurate measurements of the signal gain and noise figures of the optical amplifiers.

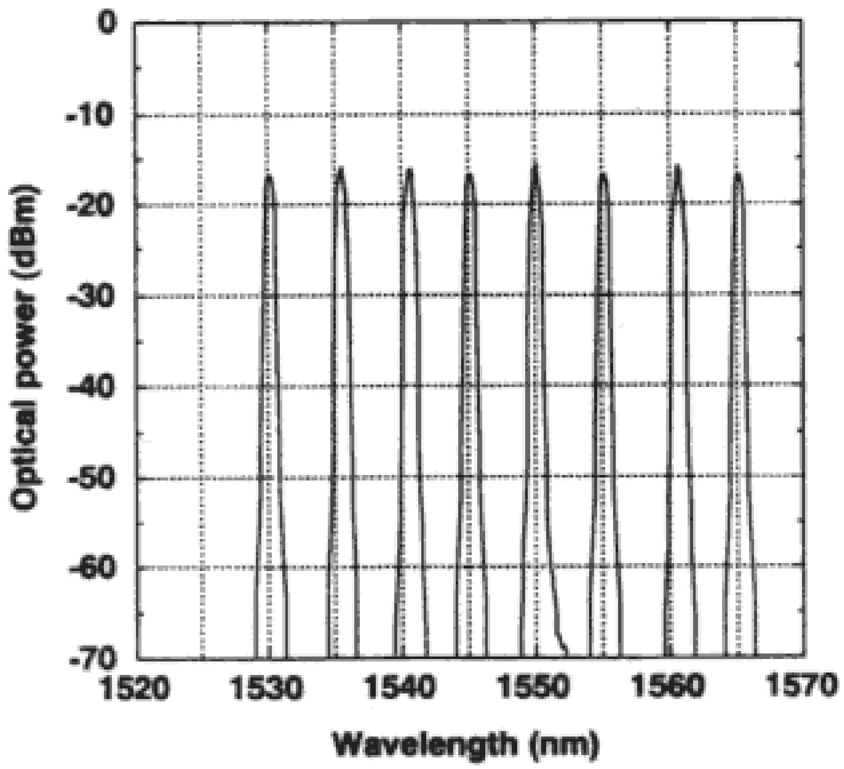

Figure 6: Output Spectrum of Multi Wavelength Light Source

ASE light sources have also been used in the non-telecom market, which includes the optical sensing system and medical applications. Figure 7 illustrates an example of an optical sensing system using a 1.5 μm ASE light source and Fiber Bragg gratings (FGBs). The basic idea is that the FBGs are placed in a location such as tunnels, bridges or rivers where data needs to be monitored. Any change that can be transferred into the change in stress
can be monitored as the change in the wavelength, which is reflected from FBGs. Due to the high brightness and broad bandwidth of the ASE, this system can be deployed for various sensing applications. The broad spectrum results in short coherence length. Another non-telecom application utilizes this nature for medical applications such as Optical Coherence Tomography to monitor the internal microstructure within the biological tissues.

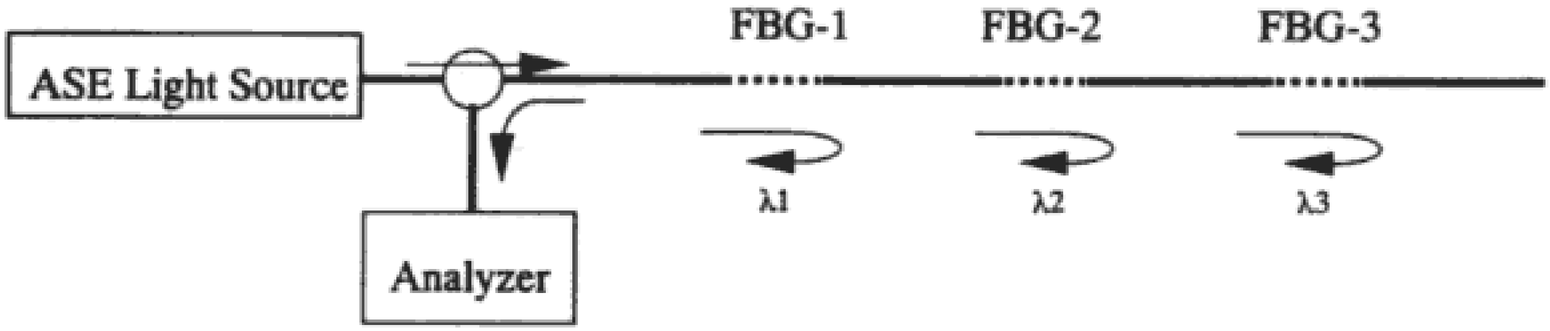

Figure 7: Schematic diagram of sensing system using ASE light source and FBGs.

3. OPTICAL AMPLIFIER

While Er-doped silica fiber has been widely used as an optical amplifier for the 1.5 μm region, the Er-doped fluoride fiber amplifier has advantageous features due to its high emission efficiency and smooth emission spectrum. Figure 8 shows the typical characteristics of the Er-doped fluoride fiber amplifiers (AMP-FL8022-CLB-xx). This instrument utilizes a unique optical design based on Er-doped fluoride fiber that is optimized to provide a spectrally flat gain profile, high signal gain, and a low noise figure over the wide bandwidth.

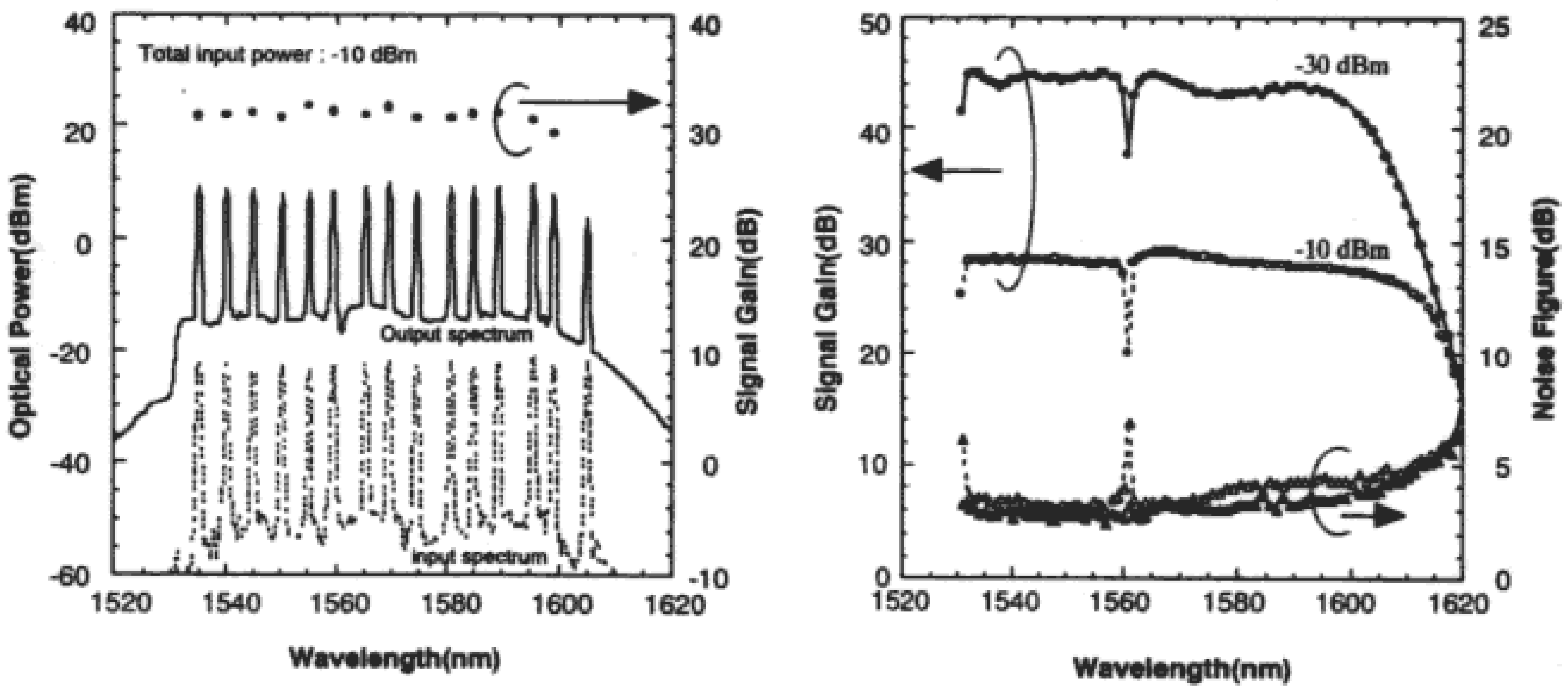

Figure 8: Amplification characteristics of 1.5 μm band amplifiers.
AMP-FL8022-CLB-W (left) and AMP-FL8022-CLB-B (right).

As there is demand for the capacity of the WDM system to be increased, the transmission window needs to be expanded to new bands. In fact, extensive research and development on the S-band are under way. For amplification at the S-band, the Raman amplifier and Tm-doped fluoride amplifier are two major approaches developed so far. Regarding the Tm-doped fluoride amplifier, a couple of schemes have been proposed, which include pumping at 800 nm, 1050 nm, 1400 nm, and dual wavelength pumping [1-4]. Depending on the scheme, the composition of the host glass needs to be optimized as well as the dopant concentration and fiber parameters. Figure 9 shows gain spectra of the 1.4 μm amplifier FL8201, which is pumped with a single 800 nm LD to produce 30 dB gain in the S-band. Figure 10 shows gain spectra of the Tm-doped gain module pumped by dual wavelengths, first demonstrated by Kasamatsu, where the shift of the gain peaks can be observed by changing pumping powers [4]. The amplification characteristics depend on the fiber as well as the pumping scheme.

Although currently, the C- & L-band amplifier and the S-band amplifier are commercially available, in terms of the gain bandwidth, a gap exists between the C- band and the S-band. Hence, one of the biggest challenges is to develop an amplifier, which can amplify the signals from the S-band through the L-band. It is believed that such an amplifier can be achieved by further improvement of the fiber itself including the fiber material, dopant concentration and fiber parameters together with an optimization of the pumping scheme. Figure 11 shows the preliminary results on the amplification centered around 1490 nm. Since more than 25 dB gain has been obtained at 1460nm thorough 1530 nm, by combining currently available amplifiers operated in the S-band and those operated at the C-band and the L-band, amplification of the entire wavelength ranging from 1440 nm up to 1610 nm is expected.

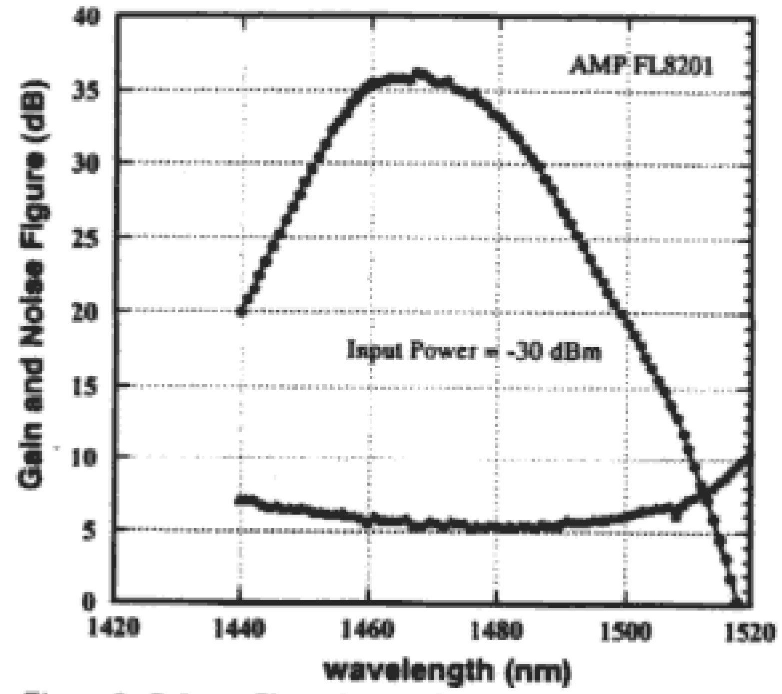

Figure 9: Gain profile and noise figure of 1.4 μm amplifier.

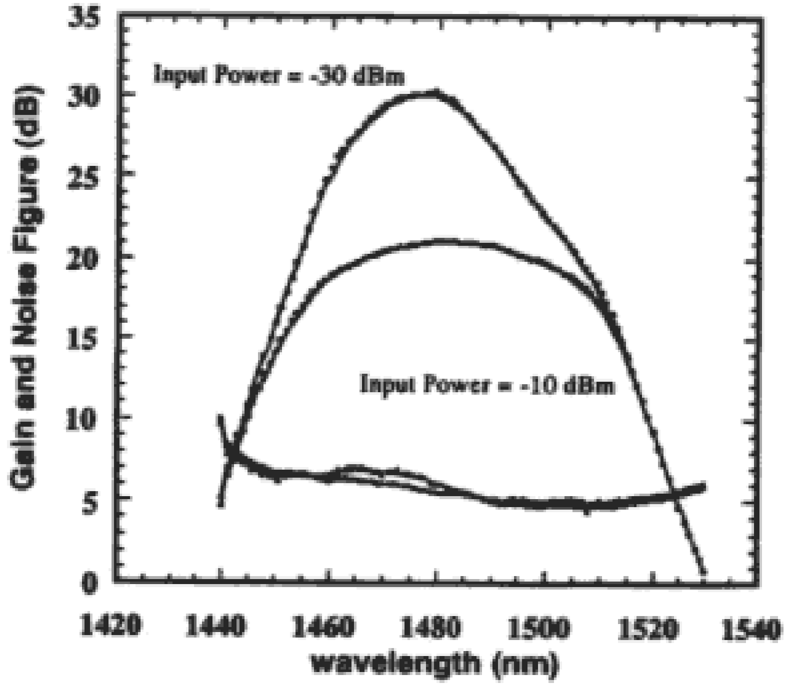

Figure 10: Gain profile and noise figure of Tm-doped gain module. Pumped at 1570nm (40 mW) and 1400 nm(190mW).

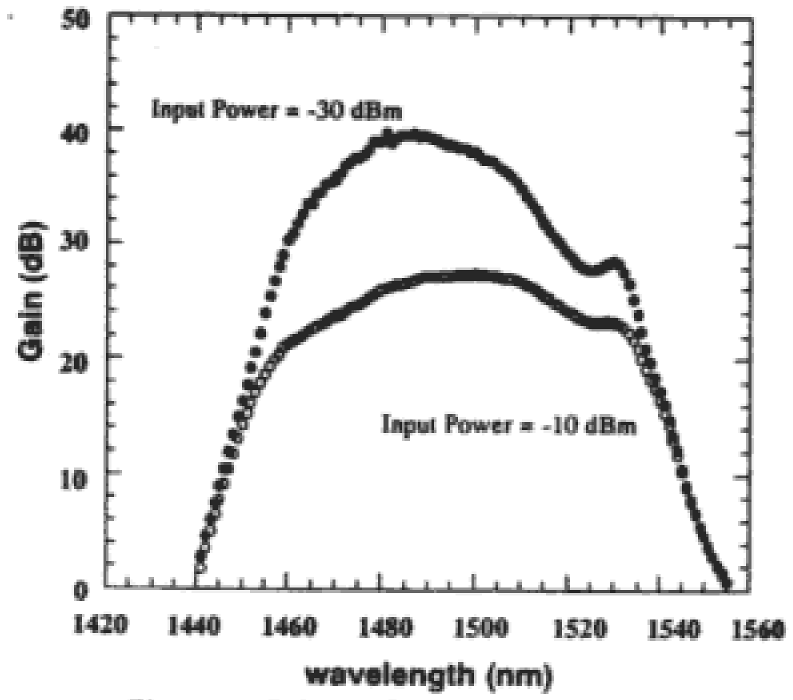

Figure 11: Gain profile of new S-band amplifier.

Another interesting feature of the fluoride fiber, which should be noted and might be useful, is the fact that the fluoride fiber can be doped with a high density of the dopants. For example, since the fiber can be doped with 10,000 ppm through 100,000 ppm Er, the short length of the fiber can provide enough gain, which might be useful for the amplification of the short pulses where the dispersion should be minimized.

4. FIBER LASER

Low phonon energy in fluoride fiber enables high conversion efficiency when a fiber laser is constructed with the fluoride fiber. Also, transparency in the near infrared region enables the fiber lasers operated in the 2-3 μm region. In fact, more than 1 W output power at 2.7 um has been reported [5,6]. Currently, fluoride fiber lasers oscillating at 1050 nm, 1950 nm, and 2050 nm are being supplied. The fiber laser at 1050 nm is made of Nd-doped fiber pumped at 800 nm, while the lasers at 1950 nm and 2050 nm are made of Tm and Ho co-doped fibers pumped at 800 nm. Figure 12 shows the relation between the pumping power and the output power of the fiber lasers, and as can be seen, about 50% emission efficiency is obtained with these fibers. Since the output power comes out of single mode fiber, it can be easily delivered to any location. In addition, the collimation of the output beam can be easily done because the output beam is transversally and longitudinally single mode.

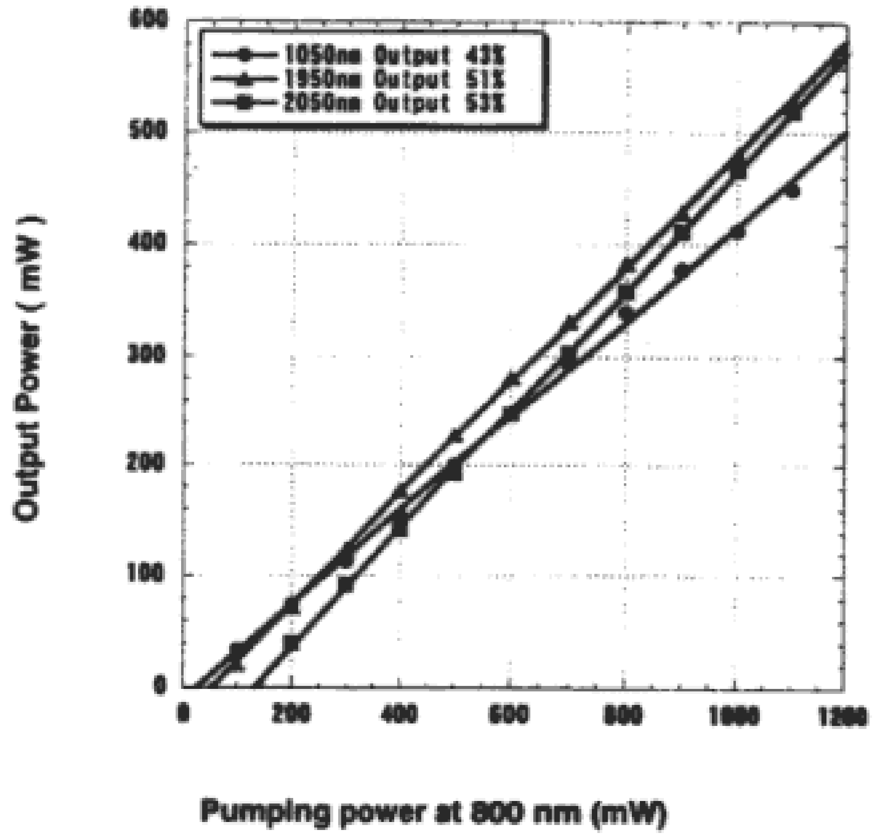

Figure 12: Output power of fiber lasers vs. pumping power

5. CONCLUSION

Some of the fluoride fiber based devices have been reviewed. The ASE light sources already enjoy widespread use in various industries, and it is believed that the application area will continue to expand. Also, the emission range will continue to expand beyond the S-, C-, and L- band. The amplifiers also will continue to find new application areas where the intrinsic nature of the fluoride fiber can determine its own value. The fiber laser is quite a new product, and it is hoped unique wavelengths available from fluoride fibers can be used to explore new applications. There had been concerns over the reliability issue related to fluoride fibers, but in the opinion of the authors this is believed to have been overcome by advanced module techniques, and, probably the most convincing evidence for the reliability is the fact there have been no failures reported in the fiber module after supplying almost 1,000 units.

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