21.9 THz-wide Ytterbium Doped Fiber Amplifier for 1 µm Data Transmission

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Abstract: We present an ultra-wideband ytterbium-doped fiber amplifier optimized for 1 µm data transmission, providing a remarkable 21.9 THz bandwidth (1025-1110 nm), with >20 dB average gain and <5.1 dB noise figure. © 2024 The Author(s)

1. Introduction

Enhancing data capacity in single mode fiber transmission systems is a key focus, and bandwidth extension plays a pivotal role in achieving this. While expanding the spectral window from the C-band (~4.4 THz) to the C+L band is a well-established solution for long-distance transmissions [1], innovative multi-band approaches are now emerging. These approaches are integrated within wavelength-division multiplexing (WDM) systems, where diverse wavelength bands are combined and transmitted over a single optical fiber. In recent developments, there have been concerted efforts to combine the C-band with neighboring E-, S- and L-bands, enabling the transmission of wideband signals spanning over 20 THz (~200 nm) [2,3]. These multi-band systems necessitate the fusion of different amplification technologies to cover E-, S-, C- and L-bands. For instance, the integration of C+L band erbium-doped fiber amplifiers (EDFAs) with thulium doped-fiber amplifiers (TDFAs) and bismuth-doped fiber amplifiers (BDFAs) has been instrumental, in showcasing transmission across the E, S, C, and L-bands over a 212 nm bandwidth (~27.8 THz) [3]. It is worth highlighting that, except for EDFAs, which have reached a significant level of maturity, other amplifier technologies exhibit various limitations. For example, despite significant advancements in recent years, BDFAs are associated with lower efficiency and typically requires 100 m lengths of gain fiber [4].

The 1 µm window has historically been disregarded for practical data transmission due to the relatively high propagation losses in conventional silica fibers (e.g. 1.5 dB/km at 1060 nm for HI1060 fiber). However, recent advancements in low-loss hollow-core fiber (HCF) operating around 1 µm (0.30 dB/km at 1060 nm) have paved the way for considering 1 µm data transmission [5]. It is important to note that ytterbium-doped fiber amplifiers (YDFAs) offer significant advantages, including wide bandwidth (note 1 nm of spectral width at 1 µm is roughly equivalent to 2 nm at 1.55 µm in frequency terms), high output power, excellent power conversion efficiency, and high gain [6]. Additionally, the availability of mature high-power fiber laser technology means that 1 µm optical components, such as modulators, passive components, and cost-effective silicon detectors, tailored for 1 µm applications are already commercially available.

In this paper, we introduce an ultra-wideband YDFA that combines two YDFAs operating in different windows (1025-1072 nm and 1075-1110 nm) in a parallel configuration, similar to C+L band EDFAs. For the 1025-1072nm YDFA, a dual stage configuration was utilized, incorporating a dielectric thin-film-based gain flattening filter (GFF) as an interstage component. For the 1075-1110 nm YDFA, a relatively lengthy gain fiber (60 m) was employed, coupled with a hybrid pumped dual-stage configuration to ensure high gain and a low noise figure (NF). By combining these two amplifiers, we achieved a wideband YDFA spanning the wavelength range 1025-1110 nm (~21.9 THz), nearly 5 times the bandwidth of a C-band EDFA. Our amplifier shows great advantages in utilizing a much simpler amplification scheme for >20-THz bandwidth whilst providing excellent gain and NF performance compared to recent works which exploited multiple bands in conjunction with the use of various amplification technologies for data transmission [2,3].

2. Experimental setup

Fig.1(a) presents the schematic of our ultra-wideband YDFA, designed similarly to C+L band EDFAs. This configuration combines two distinct YDFAs that are denoted as YDFA-1 operating from 1025-1072 nm and YDFA-2 from 1075-1110 nm. To generate a broadband seed source, we developed an in-house system that includes a multi-channel ASE comb source filtered by a programmable waveshaper in the 1025-1072 nm range, alongside a homemade tunable laser source (TLS) constructed from a Yb-doped fiber ring laser operating within the 1075-1110 nm range. Fig.1 (b) shows the spectrum of this integrated seed source which exhibits 1-dB spectral intensity variation from 1025 to 1072 nm. The total input power from the multi-channel signal was set to -5.5 dBm, corresponding to an input power per channel of -20 dBm. The single-channel TLS was set to the same spectral density and could be tuned from 1075-1110 nm. This seed source was then divided into two parallel fiber paths using a WDM splitter. In YDFA-1, two amplification stages were employed, utilizing YDF (iXblue, IXF-YDF-6-125) with different lengths (3m and 6 m, respectively), and both stages were forward-pumped by 980 nm single-mode (SM) laser diodes (LDs) with an output power of 300 mW. To minimize the gain variation, a custom-made dielectric thin-film-based GFF was introduced as an interstage GFF. At the long wavelength region (1075-1110 nm), YDFA-2 employs a hybrid pump scheme with a dual-stage configuration. The first-stage amplifier was core-pumped with a 5 m-long fiber at a pump power of 300 mW to ensure good NF performance, while the second-stage amplifier is cladding-pumped to provide efficient power conversion. In our experiment, a 60 m-long double-clad YDF (nLIGHT, DCF-YB-6/125) with a core numerical aperture (NA) of 0.12 and a cladding NA of 0.48 was used. The pump absorption at 920 nm was 0.55 dB/m. The double-clad YDF was forward pumped by a 915 nm multi-mode (MM) LD at a pump power of 600 mW to enhance power conversion efficiency at longer wavelengths and to achieve better gain uniformity over the fiber length. The amplified signals, separately amplified in the individual arms, were combined through another WDM combiner at the output port of the amplifier. The performance of this wideband YDFA was characterized by a power meter and an optical spectrum analyzer. The insertion loss (IL) from isolators and WDM couplers are below 1 dB and 0.5 dB, respectively.

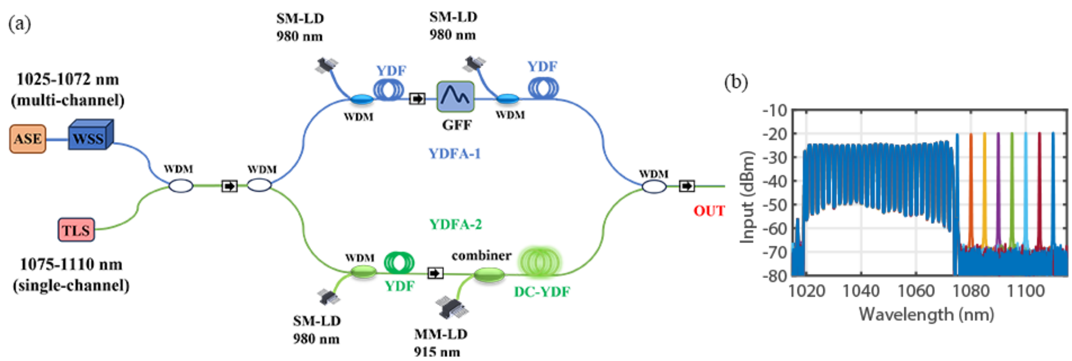

Fig. 1. (a) Schematic of the ultra-wideband YDFA and (b) the input spectrum of the seed source.

3. Results and Discussion

We first analyzed the performance of the dual-stage YDFA without a GFF. In Fig. 2(a), the red scattered points represent the measured gain and NF spectrum of YDFA-1 without a GFF, compared to our simulation results (black curve). In the absence of the GFF, the YDFA-1 demonstrated a maximum gain of 28.2 dB at 1038 nm but exhibited significant gain variation of 13.2 dB. To mitigate this substantial gain variation, we designed and fabricated a customized GFF. The inset figure in Fig. 2(b) illustrates the GFF profile, featuring the attenuation peak at 1035 nm with a peak attenuation of 9.7 dB, and matching the gain peak of the amplifier. The GFF exhibited an IL of ~0.5 dB and a polarization dependent loss of <0.1 dB. By incorporating this GFF between two amplifiers, YDFA-1 achieved a significantly reduced gain variation of 4 dB, with an average gain of 23 dB, as shown in Fig.2 (b). The measured NF remained consistently low, at < 4.2 dB. Notably, the maximum attenuation of the GFF was 2.5 dB lower than our initial design (orange curve), indicating the potential for further improvement in gain variation in the future. Nevertheless, this GFF offers compact, low-loss integration with minimal polarization dependency.

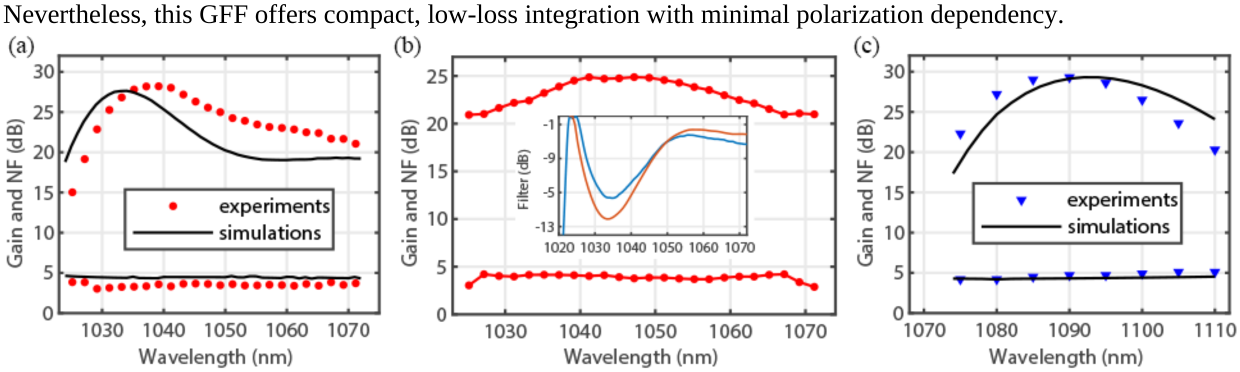

Fig.2 Gain and NF spectrum of YDFA-1 in the 1025-1072 nm range (a) without GFF and (b) with GFF, along with the filter spectrum of the GFF (inset figure, bule curve: measured, orange curve: designed). (c) Gain and NF spectrum of YDFA-2 in the 1075-1110 nm range.

In Fig. 2(c) we present the measured gain and NF spectrum of YDFA-2 (blue scatter points), which closely align with our simulations (black solid line). YDFA-2 achieved a maximum gain of 29.3 dB at 1090 nm and maintained a gain of >20 dB for signals in the 1075 to 1110 nm range. The NF remained below 5.1 dB, representing a 1.4 dB improvement compared to the single-stage cladding-pumped YDFA discussed in [7]. It is worth noting that the NF in this wavelength range is 0.9 dB higher than that in the 1025-1072 nm region, primarily due to the slightly increased IL of passive components, such as isolators and WDM couplers, at longer wavelengths.

These two YDFAs are combined in a parallel configuration, and Fig.3(a) presents the measured overall gain and NF spectrum in the 1025-1110 nm range. The combination of 47 nm gain region from 1025 to 1072 nm and another 35 nm from 1075 to 1110 nm results in an exceptionally broad overall gain spectrum spanning 82 nm. This translates to a frequency bandwidth of ~21.9 THz, nearly double that of C+L band EDFAs. Fig. 3(b) displays the output spectrum across the entire wavelength range, showcasing an output OSNR of >20 dB for most signal channels.

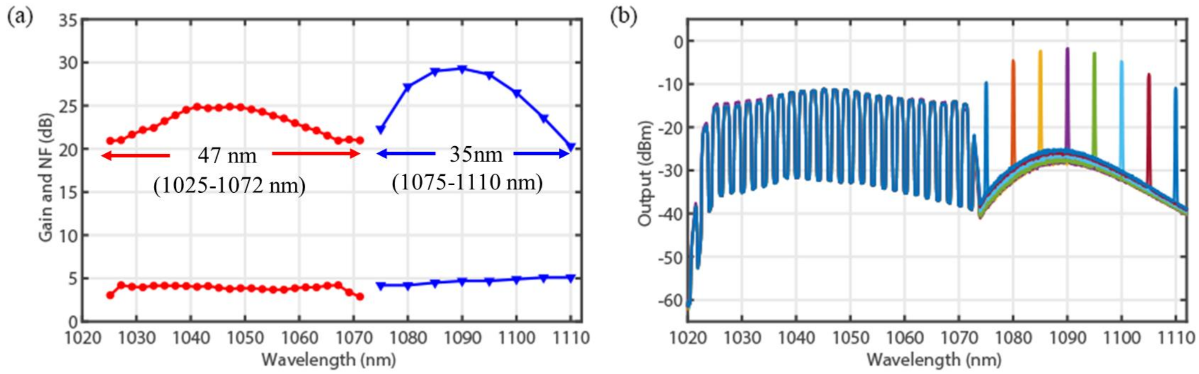

Fig.3 (a) Overall gain and NF spectrum in the 1025-1110 nm range and (b) output spectrum of YDFA.

4. Conclusions

In conclusion, we have successfully demonstrated an ultra-wideband YDFA specifically designed for 1 µm data transmission. This innovation combines two YDFAs in different operating windows, akin to the C+L band EDFA. Notably, this amplifier delivers an outstanding 21.9 THz bandwidth within the 1025-1110 nm range, representing nearly a five-fold increase over conventional C-band EDFAs. The exceptional optical performance of our amplifier is underscored by its average gain of >20 dB and a maximum NF of 5.1 dB. This advancement should support significantly enhanced data transmission in the 1 µm waveband and represents a promising approach to meet the growing demands for high-capacity data transmission in a compact and efficient manner.

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