Erbium-Doped Waveguide Amplifier (EDWA) Technology and Components

Jacob L. Philipsen (1), Carsten L. Thomsen (1), Lasse Leick (1), Yueqiang Shen (1), Peter C. Nielsen (1), Christian Laurent-Lund (1), Morten G. Dyndgaard (2), Thomas Feuchter (1)
(1): NKT Integration A/S, Blokken 84, DK- 3460 Birkerød, Denmark, E-mail: jph@nktintegration.com
(2): COM, Technical University of Denmark (DTU), Building 345V, DK- 2800 Kgs. Lyngby, Denmark

Abstract: *EDWA technology is now commercially available and forms a compact and cost-effective alternative to the EDFA as a key building block for amplifying and controlling signal power in multifunctional subsystems-on-a-chip. We review the current status of EDWA technology and its applications.*

Introduction

Optical amplification with Er-doped glass as the gain medium has been a key enabler for Dense Wavelength Division Multiplexed (DWDM) optical transport systems. Leveraging on the fundamental properties of Er in a glass host, the Erbium Doped Fiber Amplifier (EDFA) has demonstrated high gain, low noise, and full compatibility with DWDM signals.

Presently important trends in optical telecom are the evolution from point-to-point transport systems towards optical networks and the evolution from discrete optical components towards integrated optical solutions based on Planar Lightwave Circuits (PLC). The latter evolution is a prerequisite for the former, since the increased complexity of an optical network can only be handled in a cost-effective manner by the introduction of integrated optics and its wafer-manufacture economies of scale. In these multifunctional PLCs, amplification and dynamic power level control will be important enabling functions.

Erbium-Doped Waveguide Amplifiers (EDWAs) offer these functionalities at a low price-per-function, and this has over the past few years driven EDWA-based devices from research labs to commercialization [1, 2, 3]. This article reviews the present status of EDWAs, with focus on silica-on-silicon devices and their applications.

Process

In a waveguide amplifier, the background losses as well as the physical dimensions limit the amplifier dimensions. Making EDWAs therefore require careful selection of the host material to ensure a high solubility of Er, and EDWAs in glass hosts ranging from P-doped silica [4] and Phosphates [5, 6], over Al-doped silica [7] to pure Alumina [8] have been investigated successfully.

Phosphate glasses enable high Er concentration with a low degree of clustering, and are attractive hosts for EDWAs made by ion-exchange. Net gain of more than 2 dB/cm has been demonstrated in such glasses [5], but with a narrow gain spectrum compared to EDFAs, hence limiting the effective bandwidth.

Al-doped silica and Alumina enable high Er concentration with a low degree of clustering and provide a broad gain spectrum similar to that of Er/Al/La-doped fibers. The refractive index of Al-doped silica can be controlled by further doping with Germanium to allow low loss coupling to silica fibers and standard waveguides. We have therefore chosen Al/Ge-doped silica as the host material for manufacturing EDWAs.

Our EDWAs are formed in a three layer structure. The substrate is a 6 inch Silicon wafer with a layer of thermally grown silica. The Er-doped core layer may be deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) [9], flame hydrolysis [4] and sputtering [7, 8]. We have chosen the PECVD process as this yields excellent uniformity of thickness and refractive index. Furthermore, the process is a rapid, low temperature process with very low surface migration of the Er ions, which minimizes the formation of Er-clusters during deposition. Er- and Al-containing precursors are added to the gas mixture during the deposition, thereby forming a Ge/Al/Er-doped silica layer with accurate control of the composition. The core layer is patterned to waveguides using photo-lithography and Reactive Ion Etching (RIE) and finally, PECVD is applied for depositing the boron and phosphorus co-doped cladding layer. The combination of advanced PECVD and RIE processes enable realization of waveguides with extremely low propagation losses as we report elsewhere [2].

For multifunctional components it is required to integrate waveguides with and without Er doping, as unpumped Er-doped waveguides have absorption at signal wavelengths. A composite core layer can be formed by a repeated series of deposition, patterning and etching processes using two complementary masks. Subsequently the composite core layer is patterned with one mask, whence the horizontal alignment between the Er-doped and undoped areas is inherently perfect. The vertical alignment depends on the precision of the etch depth and layer thickness. The achieved reproducibility of 0.1 µm gives an interface loss of 0.022 dB/interface (see Fig. 1B) and a back-reflection below -70 dB [10].

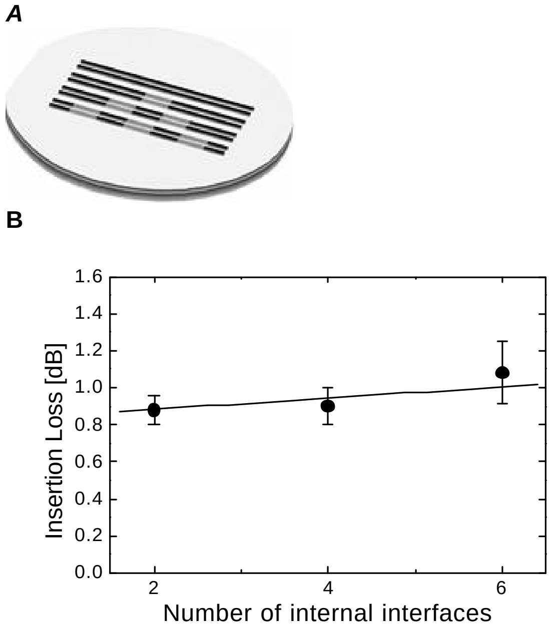

Fig. 1A: Layout of the waveguide circuitry used to measure interface loss between erbium-doped (light grey) and standard waveguide regions; fig. 1B: Loss as a function of the number of internal interfaces.

Performance

To achieve sufficient length, our planar amplifier is curled up in a spiral. By optimizing both fabrication and design we have achieved an ultra-low propagation loss of 0.015 dB/cm [2]. This enables high gain as it allows for longer amplifiers with lower Er-concentration, thus increasing the efficiency of the Er-ions [11].

Fig. 2 shows the measured gain and noise figure spectra with -30 dBm input power and 100 mW of 980 nm pump power.

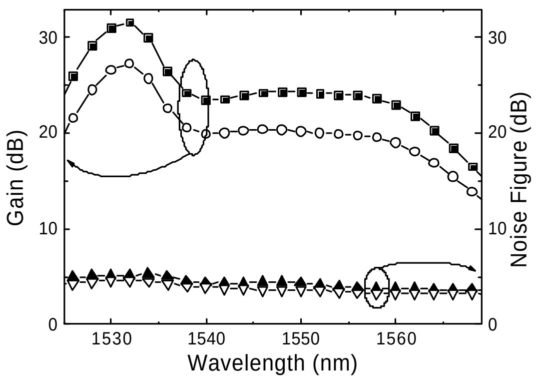

Fig. 2: Measured gain (squares, circles) and noise figure spectra (triangles) for –30 dBm input power and 100 mW of 980 nm pump for an optimized and a test EDWA (closed / open symbols).

The graph contains data for an EDWA optimized for high gain (closed symbols) and a 40% shorter test EDWA (open symbols). The optimized EDWA has a peak gain of 31.5 dB (1532 nm), a C-band (1528-1562 nm) gain of 23 dB and a C-band noise figure of 5.3 dB. In comparison the test EDWA has 18 dB C-band gain and a noise figure of 4.6 dB. The slight increase of noise figure at high gain is caused by the backwards traveling ASE reducing the population inversion at the amplifier input.

To measure the gain spectrum at higher input powers, a 1550 nm laser is used to saturate the EDWA. The saturation laser is multiplexed with a weak input probe signal prior to the EDWA and the signal gain is inferred from a measurement of the EDWAs output spectrum. Fig. 3 shows the measured gain and noise figure spectra with -10 dBm input power and 100 mW of 980 nm pump power. Fig. 3 contains data for the same EDWAs as fig. 2. The EDWA, which was optimized to small input signal, has a C-band gain of 17.4 dB and a noise figure of 4.7 dB, whereas the shorter test EDWA has a C-band gain of 15.8 dB and a noise figure of 4.0 dB. A comparison with fig. 2 shows that the difference in gain between the EDWAs has decreased with the signal power. The reason is that the optimum EDWA design depends on the signal levels and that an increase in signal power moves the optimum towards shorter length. Furthermore the noise figure has decreased with the signal power due to reduced backward ASE.

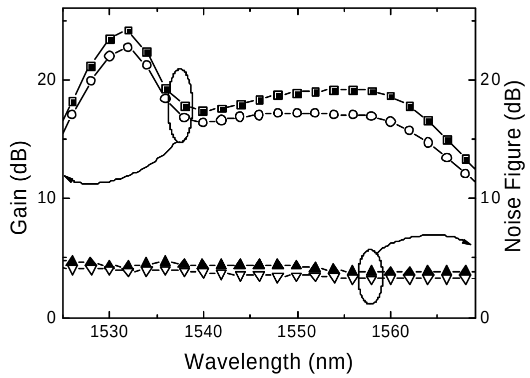

Fig. 3: Measured gain (squares, circles) and noise figure spectra (triangles) for -10 dBm input power and 100 mW of 980 nm pump for an EDWA, which is optimized for small signal power, and a test EDWA (closed / open symbols).

At further saturation, an input power of 0 dBm leads to an output power of 7-7.5 dBm for the above described EDWAs, whereas an EDWA optimized with respect to output power gives 10 dBm, corresponding to a conversion efficiency of 10%.

Comparison between different EDWA technologies is difficult as the field is dominated by commercial vendors, whence results are not published. However, to the best of our knowledge the 23 dB C-band gain with 100 mW of pump power is the highest single-pass small signal EDWA gain ever reported.

Modeling

In contrast to Er-doped fibers, the EDWA length is defined during the fabrication, which limits the possible post fabrication adjustment to changing the pump power. Hence a reliable numerical model is required for optimization of EDWAs before fabrication. As no accurate commercial software exists we have developed our own numerical model. The model takes ion-ion interactions into account [11]. Experimental values were used for the upconversion constant, the propagation loss, the fiber to chip coupling loss, the Er cross-sections and the Er concentration. The pump and signal field distributions were calculated with an effective index method and it was verified that the measured and calculated optical mode profiles are similar. The model includes forward and backward amplified spontaneous emission (ASE) in the signal band. The coupled differential equations for the pump, signal, and ASE intensities are solved by iterative numerical integration along the length of the waveguide amplifier using a Fourth order Runge Kutta method. The gain and noise figure are found as described in Ref. 12 [12]. A detailed description of the model can be found in Ref. 13 [13].

To validate the model we have compared the measured and simulated EDWA performance. Fig. 4 shows the measured and simulated peak gain as functions of the pump power for three different input signal levels. The agreement between the measured and simulated values is excellent. For small pump powers the gain increases rapidly with pump power and optical transparency is reached at 20-30 mW. At larger pump powers of ~100 mW, the gain curve flattens out, and at a pump power of 400 mW, a maximum gain of 40 dB is obtained, both for calculated and measured results.

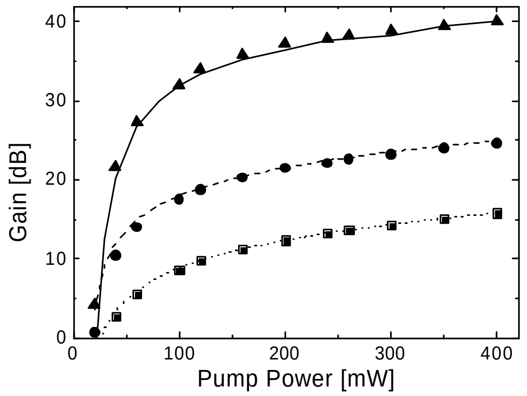

Fig. 4: Measured (symbols) and simulated (lines) peak gain as functions of the pump power for input signals of -30 dBm (triangles), -10 dBm (circles) and 0 dBm (squares). The EDWA design is optimized for small signal gain with 100 mW of pump power.

The figure demonstrates that our model is accurate and can be used under a large number of different conditions. Hence it provides us with a valuable tool for designing EDWAs to meet any required specification.

Applications

The simplest application of EDWA technology is a single amplifier including passive functions such as input and output tap couplers, pump/signal multiplexer, and pump kill filter on a single chip. Both single channel and DWDM amplifiers for metro and pre-amplifier applications have been demonstrated [1, 3]. However, pushed by the price pressure from low-cost EDFAs, this mainly has niche applications, such as integrated pre-amplifiers in receivers, in which the reduced form factor is a decisive competitive factor.

Next step will be the integration of EDWAs with other passive functionality. Figs. 5 and 6 show the combination of a DWDM EDWA preamplifier with a 40-channel AWG demultiplexer. The EDWA and AWG devices were realized on separate chips, but with fully compatible (Er-doped respectively undoped) manufacturing processes, allowing for monolithic integration as described in section 2 of this article. Over the C-band, the inferred combined gain for the EDWA/DEMUX varies from 15.6 dB (1540 nm) to 22.1 dB (1532 nm), measured at channel peaks. The EDWA/DEMUX represents a very cost-effective way of enhancing DWDM receiver sensitivity, since the monolithic addition of an EDWA to the AWG DEMUX implies virtually no extra pigtailing and packaging cost (apart from the cost of a discrete pump laser and an isolator). For this type of integration, PECVD-processed silica-on-silicon PLCs have the advantage of allowing the very high process uniformity required to make state-of-the-art AWGs.

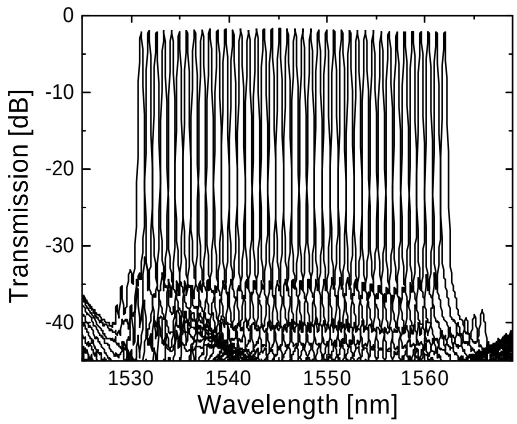

Fig. 5: Measured transmission spectrum of a 40 channel 100 GHz AWG. The chip minimum insertion loss is 1.6 dB and the channel uniformity 0.6 dB. The adjacent channel crosstalk is 29 dB; the non-adjacent cross-talk is 35 dB.

As integrated optics evolves from single-functionality chips (splitter, Arrayed Waveguide Grating (AWG) etc.) towards multifunctional subsystems-on-a-chip (Variable Multiplexer (VMUX), Reconfigurable Optical Add-Drop Multiplexer (ROADM) etc.), the EDWA will become a key building block for amplifying and controlling signal power levels. Control may be obtained by adjusting the pump power to the EDWA to achieve the desired output signal power. Compared to the classical scheme of adjusting signal powers by Variable Optical Attenuators (VOA), the "Variable Optical Amplifier" has the advantage of an improved power budget and improved system signal-to-noise ratio, because channel powers are equalized by being raised to a common high level instead of being decreased to a common low level.

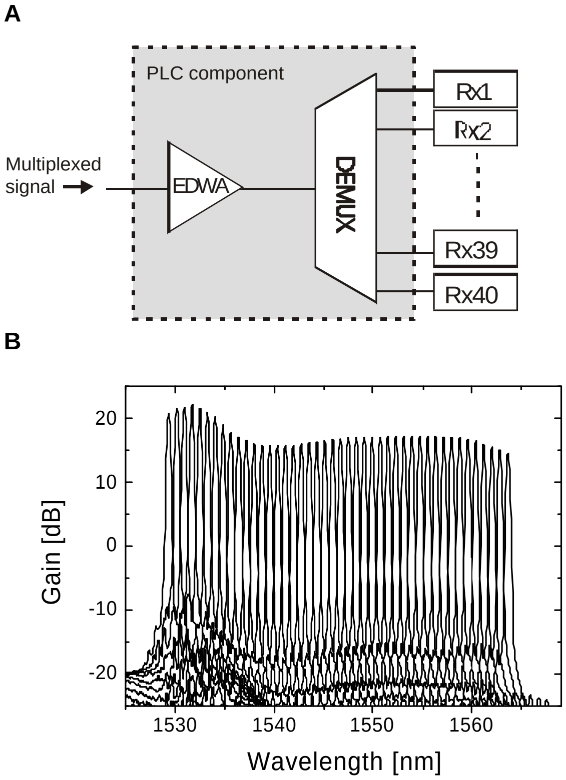

Fig. 6A: Schematic view of the integrated EDWA and AWG DEMUX; fig. 6B: Inferred spectrum for EDWA/ DEMUX device, based on the individual, measured spectra. The average input power of each of the 40 channels is -26 dBm, corresponding to a combined power of –10 dBm. The EDWA is pumped by 100 mW at 980 nm.

An example of such an application is the monolithically integrated 4- or 8-port EDWA array demonstrated by several commercial companies. The purpose of this device is to provide individual amplifier control in applications with a single-channel or a band of channels passing through each amplifier. Applications include preamplifier arrays and dynamic gain equalization at wavelength switching nodes such as ROADMs. The desire to standardize such a compact amplifier array module has led to the formulation of a Multi Source Agreement (MSA) for EDWA Arrays [14]

An interesting combination of individual channel gain control and multiplexing is the integration of colorless AWGs (typically 4-8 channels) with equivalent port count EDWA arrays for individual channel power control and a high combined output power. With 10 dBm output power from each amplifier and approximately 3 dB MUX and output pigtailing loss, an aggregate output line power of 16 dBm will be obtainable for an 8-channel colorless EDWA/MUX. This is comparable to in-line EDFAs, but with the full channel control of a Dynamic Gain Equalizer (DGE).

Conclusion

We have presented a status on EDWA technology, with focus on PECVD-manufactured amplifiers, and have reported a small-signal gain of more than 23 dB over the C-band, obtained with 100 mW of pump power in an extremely low loss Er-doped Al/Ge silicate waveguide. We have also reported a state-of-the-art AWG, which is processed with the same wafer process excluding Er-doping. In summary, EDWA technology has reached a level of performance and maturity that will allow a larger focus on developing applications, such as loss-less/amplifying Planar Lightwave Circuits with advanced functionality.

References

1 J. L. Philipsen et al, Proc., OAA 2000. OTuD2.
2 Leick et al, Submitted to ECOC 2003
3 Product information on the web-sites: www.nktintegration.com, www.teemphotonics.com, and www.inplane.com
4 K. Hattori et al, Electron. Lett. Vol. 30 (1994), 856.
5 D. Barbier et al, Tech. Dig. OFC'98, San-Jose, 1998, TuH5, p.45.
6 Y. C. Yan et al, Appl. Phys. Lett. Vol. 71 (1997), 2922.
7 J. Shmulovich, et al, Techn. Dig., OFC ´99, PD42-1.
8 G. N. Hoven et al, Appl. Phys. Lett. Vol. 68 (1996), 1886.
9 J. Hübner et al, Appl. Phys. B Vol. 73 (2001), 435.
10 C. Laurent-Lund et al, IEEE Photon Technol. Lett., Vol. 10 (1998), 1431
11 J. L. Philipsen, Ph.D. thesis, COM, Technical University of Denmark, 1999
12 A. Bjarklev, "Optical fiber amplifiers; Design and system applications", Artech House, 1993
13 M. G. Dyndgaard, Ph.D. thesis, COM, Technical University of Denmark, 2001
14 "Reference document for compact amplifier array", MSA document by NKT Integration and Teem Photonics. February 2003