# Multi-Element Fiber for Space-Division Multiplexing

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**Abstract**. A novel approach of using multi-element fiber (MEF) technology in space-division multiplexing (SDM) systems is presented. This paper reviews the progress in fabrication and characterization of MEF based both ultra-low crosstalk transmission and amplifier fibers. Passive 3-element MEFs have been successfully demonstrated for application in telecommunications. An active 5-element MEF amplifier has also been demonstrated in a novel multi-port cladding-pumped configuration, in which a central un-doped multi-mode pump fiber-element is surrounded by four Er/Yb-doped active fiber-elements. MEF is compatible with current WDM systems, and there is no need to develop specialized multiplexing/demultiplexing components. Moreover, it offers a smooth upgrade to SDM systems.

**Keywords**: SDM, MEF, EDFA, Multi-port amplifier, transmission, fiber, cladding-pump, split C+L-band amplifier

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## 1 Introduction

The rapidly increasing demands for more and faster data traffic will exhaust the available capacity of standard single mode fibers (SMF) in the near future, and there is a strong need to cope with this future demand in the most economic manner. Space-division multiplexing (SDM)[1,2] based transmission systems have been considered as an intuitive approach for overcoming the capacity limit of existing SMF.

The approaches followed so far to implement SDM are mainly based on either multicore fiber (MCF) or few-mode fiber (FMF). Significant advancements have been made in data transmission rates through both of these technologies[1]. Orbital angular momentum (OAM) multiplexing for data transmission has also been explored[3].

In MCF[4], which is defined by the multiple cores placed in a common cladding, independent data channels are transmitted in parallel through the multiple cores, thereby, increasing the transmission capacity per-fiber as compared to SMFs. However, the number of cores is limited by the core-to-core separation (for low-crosstalk operation) as well as the overall cladding diameter limit of around 225μm in order to maintain long-term mechanical reliability of the fiber. At larger diameters silica fiber is more susceptible to failure. Various MCF designs have been proposed to reduce crosstalk in order to increase the core-density in the fiber[5-8]. Currently, the maximum number of cores is limited to 13 due to the above mentioned restrictions[9]. In addition, MCF requires specialized fan-in and fan-out components for accessing the individual cores[10]. These impairments hinder the full usage of the cost benefit offered by SDM implementation. There have been various demonstrations of MCF based core[11,12] and cladding pumped amplifiers[13,14], but these devices also require specialized couplers to access the cores.

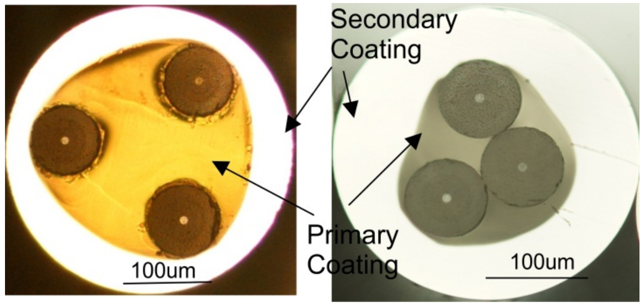
FMF, on the other hand allows parallel data transmission through different propagation modes in the core[15]. This technique can also be applied in MCFs by using multimode cores to take the advantage of both multiplexing schemes. However, mode coupling in MMF based transmission systems becomes inevitable, and multiple-input-multiple-output (MIMO) processing is necessary to decouple the signals. This leads to a significant increase in the system complexity[16] and cost. In addition, mode-dependent losses and gain cannot be fully compensated[15]. MMF based SDM systems also require the development of special couplers for launching different modes into the core[17,18]. Various FMF amplifiers suitable for mode-division multiplexed transmission have been demonstrated[19].

We present an alternative approach to implement SDM based on multi-element fiber (MEF). MEF technology can overcome many of the current limitations associated with MCF and FMF systems, while at the same time becoming cost-effective. MEF consists of multiple fiber-elements that are drawn and coated together in a common polymer coating, thereby offering a dense packaging of fibers as compared to a bundle of SMFs. The main advantage of the MEF geometry is that each fiber can be accessed independently, simply by stripping-off the polymer coating, and then conventional splicing to SMF components can be performed. Thus, there is no need for the development of specialized coupling components to access individual cores in MEF. Unlike MCF, there is also no fundamental limit expected to the overall diameter of a MEF (and associated number of elements) as long as the mechanical robustness of the individual fiber-elements is maintained. In addition, the MEF geometry ensures ultra-low crosstalk between the individual elements.

MEF geometry can also be easily extended to manufacture multi-element Erbium (Er) doped fiber amplifiers (ME-EDFA). We have already reported core-pumped ME-EDFAs, comprising 3 and 7 Er-doped fiber-elements[20] respectively. In addition, a cladding-pumped Er/Yb-doped 5-element MEF amplifier (ME-EYDFA) has been realized[21], which will lower the transmission costs per bit. In cladding-pumped ME-EDFAs, a central pump fiber is shared by several surrounding signal fibers, four in the case of the work described here. In this report, we describe the MEF fabrication technique for implementing the cladding-pumped multi-port amplifier concept for SDM systems. Furthermore, the signal fibers have been combined to make cascaded amplifiers, to achieve a flat-gain and tune the gain profile of the device. In addition, both passive 3-MEF and C-band ME-EYDFA have been tested in a SDM based transmission experiments to demonstrate the compatibility of MEF technology with existing technology[22,23].

In this paper, we review the progress achieved to-date in fabrication and characterization of passive MEFs and ME-EYDFAs. Preliminary experiments have demonstrated in transmission of 1014Gbps in a passive 3-element MEF (3-MEF) over a length of 28.5km. Both C-band and C+L split band cladding-pumped ME-EYDFA have also been demonstrated[24].

## 2 Passive 3-MEF Fabrication and Characterization:




a) b)

**Fig. 1.** Microscope images of a) non-compact (with element to element separation 90-95 μm) and, b) compact passive 3-MEF fabricated from Ge-doped preform

Fig. 1 shows the cross-sectional images of a non-compact 3-MEF, where the fiber elements are widely separated (90-95μm), and a compact 3-MEF. A conventional Ge-doped preform with an index difference (Δn) of 0.0055 with respect to the silica cladding was utilized to construct these 3-MEFs, and subsequently drawn into 9.5km and 3.07km of non-compact and compact 3-MEFs respectively with a high-index dual polymer coating, in which the Desotech DP-1004 and DS-2015 were used as primary and secondary coatings respectively. The cladding and core diameters of each fiber-element were 80μm and 8.5μm respectively. The overall coated fiber diameter for the non-compact and compact 3-MEFs were 340μm and 297μm respectively. These fibers were tested in our transmission experiments. Several test draws of compact and non-compact 3-MEF geometries with different element sizes (80 and 60 μm) and element-to-element spacing were made using CFQ (clear-fused-quartz) rods. This was to establish the 3-MEF fabrication parameters that are suitable for the manufacturing of long lengths of fiber while keeping its mechanical strength. 3-MEFs were proof tested using an industrial optical fiber rewind and proof testing machine, and the results are summarized in Table 1. It is worth noting that the same fiber drawing conditions as obtained from the test draws of non-compact 3-MEF with 95μm element spacing and compact (no-spacing) were utilized to draw Ge-doped non-compact (Fig 1a) and compact (Fig. 1b) 3-MEFs respectively.

**Table 1** Strength of different 3-MEFs fabricated using test rods

| Element spacing (μm) | Element Diameter (μm) | Proof Test Strength (Kpsi) |
|---|---|---|
| 95 | 80 | 400 |
| 55 | 80 | 400 |
| No (Compact) | 80 | ~100 |
| 95-100 | 60 | >500 |

Table 2 compares the OTDR losses measured at three different wavelengths for non-compact and compact Ge-doped passive 3-MEFs with element diameter 80μm. The OTDR loss for all three fiber-elements in non-compact MEF was similar as was measured in a single fiber drawn from the same Ge-doped preform with single-mode core and cladding diameter of 100µm. However, the loss of the compact 3-MEF was significantly higher for two of the fiber-elements than it was in the third (2.5dB/km as compared to ~0.7dB/km at a wavelength of 1550nm). Following this, a 4km length of Ge-doped 3-MEF with an element separation of about 55 µm was fabricated that exhibited a similar loss profile for all three fiber-elements as that of the non-compact 3-MEF with element separation of 95µm, confirming the scope of a dense packing of the fiber-elements in MEF.

**Table 2** OTDR loss of non-compact and compact Ge-doped passive 3-MEF

| 3-MEF (80 µm element diameter) | Length (km) | Loss at 1310nm (dB/km) | Loss at 1550nm (dB/km) | Loss at 1650nm (dB/km) |
|---|---|---|---|---|
| 95µm spacing | 9.5 | 1.6 | 0.6 | 0.7 |
| No spacing | 3.07 | 2(1-element) ~3.5(remaining elements) | 0.7(1-element) ~2.5 (remaining elements) | 0.95(1-element) ~3.5 (remaining elements) |

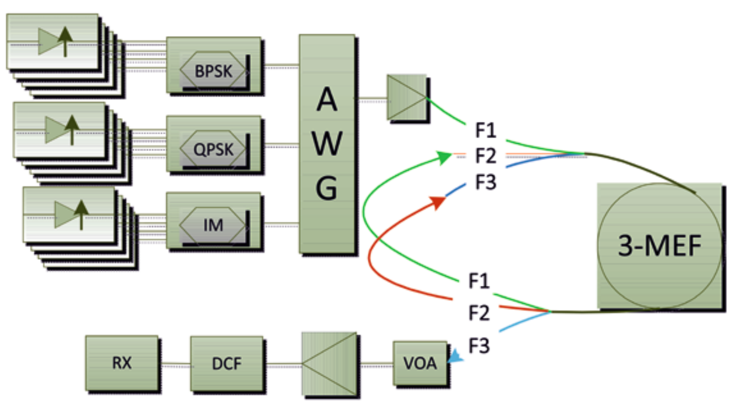



**Fig. 2.** Schematic setup for BER measurement

The calculated cut-off wavelength and measured dispersion at 1550 nm for each fiber-element was approximately 1250nm and 18-ps/nm/km respectively. The fiber-elements in non-compact 3-MEFs with an element spacing of 95 µm were subsequently connected in series with the output of one fiber-element spliced to the input of  next fiber-element of the same length of 3-MEF, thus obtaining an effective total transmission length of 28.5km, for the transmission experiment. 3-MEFs were then characterized for bit-error-rate (BER) performance using wavelength multiplexed channels in three different modulation formats: twenty-one-10-Gbps-OOK, two 40Gbps-BPSK, and two 24Gbps-Qpsk, with overall data rate of 1014 Gbps[22]. The schematic of the experimental setup for the BER measurement is shown in fig 2. Dispersion compensating fiber (DCF) was used prior to retrieving the channels at the output. 120-ps/nm of dispersion was left uncompensated due to the limited choice of tailored DCF modules available in the lab.

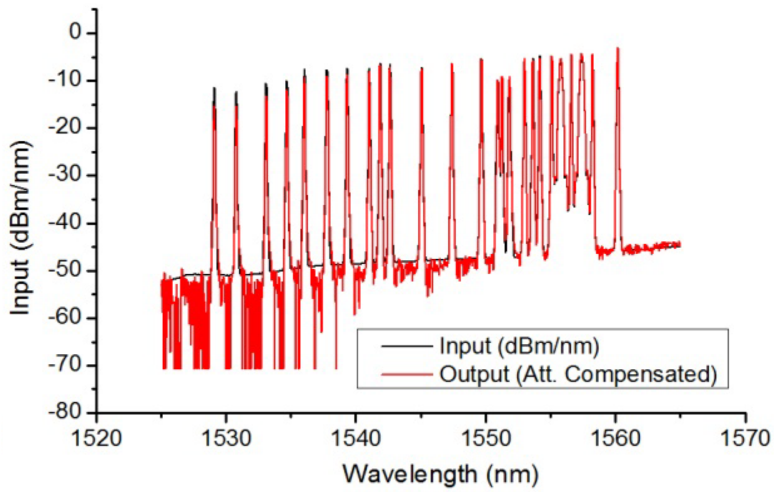
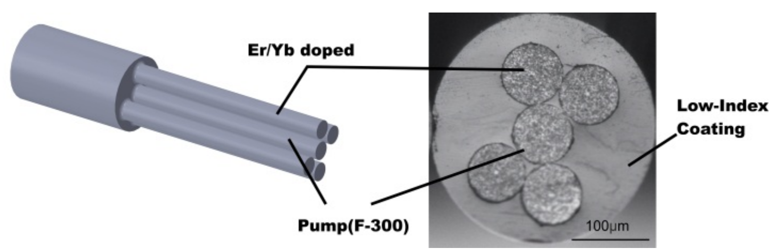



**Fig. 3.**Input and attenuation compensation output spectra for all the channels in operation.

All the channels were detected to be error-free at the output. As seen in fig. 3, the input and output spectra (attenuation compensated) of the channels launched in the MEF overlapped. This indicates negligible OSNR degradation and flat attenuation across the measured wavelength band. Also, no crosstalk (down to the level of -80 dB) was observed between the different fiber-elements when measured using a laser source at a wavelength of 1550nm.

## 3 Cladding-pump Er/Yb-doped MEF Amplifier




a) b)

**Fig. 4** a) Er/Yb-doped 5-MEF preform assembly in cladding-pump configuration and b) microscope image of the fiber cross-section.

The MEF technology was extended to develop a cladding-pumped ME-EYDFA. A 5-MEF active preform was assembled from a high quality silica rod (F300) and an Er/Yb-doped preform. The doped preform was cut into four equal lengths and assembled together with a central silica rod as shown in fig 4a. The MEF preform assembly was then drawn into fiber using a single low-index polymer coating, in which each fiber-element had a cladding diameter of 80µm. The core diameter for the signal fiber-elements was about 8µm. The overall coated diameter was 305µm. The microscope image of the 5-MEF cross-section is shown in fig. 4b. The signal fiber-elements in 5-MEF were arbitrarily coded as S1, S2, S3 and S4 respectively, and the pump fiber-element as P. The cladding absorption of the signal fiber-elements was measured using a white light source and was found to be 2.2-4.1dB/m at a wavelength of 975nm. The variation of rare-earth concentrations along the length of the Er/Yb-doped preform used in this work led to a variation in the absorption measured for different signal fiber-elements. However, this can be used advantageously to develop C+L Split-band amplifier.

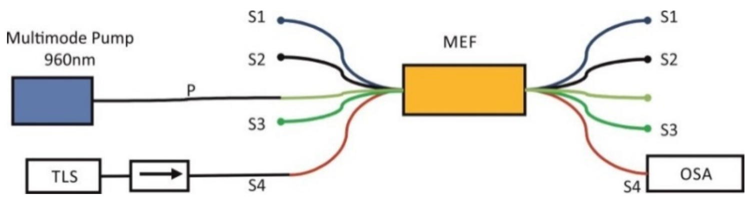
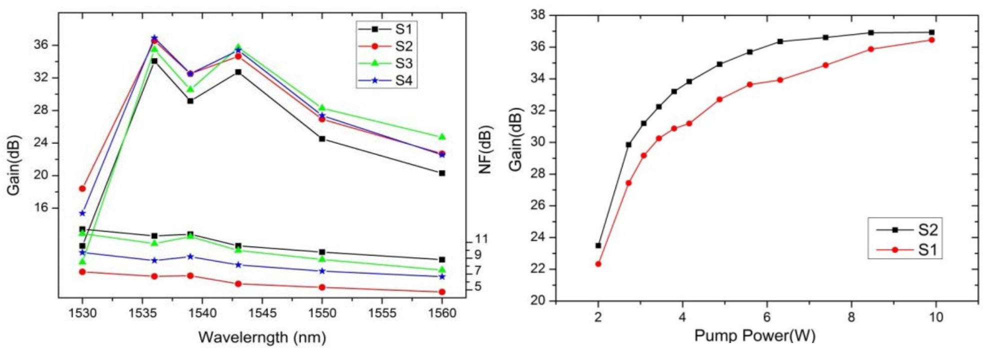



**Fig. 5** Experimental setup for gain and noise figure measurements in Er/Yb-doped MEF.

Fig. 5 shows a schematic of the experimental setup for gain and noise figure (NF) characterization of ME-EYDFA. A fiber coupled multimode pump operating at a wavelength of 960nm, a tunable laser source (TLS) covering the C + L band, and an optical spectrum analyzer (OSA) to record both the input and output signals were used in our experiment. The length of 5-MEF was 4m. Fig. 6a) shows the gain and NF performance of individual signal fibers when 6.4W of pump light was launched into the fiber-element P. A maximum gain of 35±2.5 dB was observed per signal fiber element with a minimum NF of 4.7 dB for an input signal of -23dBm. The gain increased to 37±2dB when the launched pump power was increased to 10W[21]. The pump power vs. gain curve is plotted in fig. 6b) for signal fiber-elements S1 and S2 respectively, showing that the gain saturates beyond 8W of launched pump power.




a) b)

**Fig. 6** a) Gain and noise figure variation with wavelength for MEF signal fibers at a pump power of 6.4W and input signal of -23dBm, and b) pump power vs. gain for -23dBm input signal at a wavelength of 1543nm for signal fibers S1 and S2 respectively.

The signal fiber-elements were cascaded one after another by connecting the output of one fiber-element to the input of the next fiber-element, without using any isolator in-between, and the change in the amplified spontaneous emission (ASE) and gain was measured. Fig. 7 shows the change in the ASE and gain at pump powers of 2.5W and 4.5W respectively, for the following configurations: a) S4, b) S4-S1, c) S4-S1-S2. An input signal of -23dBm was used to measure the gain at four different wavelengths; 1544nm, 1550nm, 1560nm, and 1565nm. It was observed that the bandwidth of the cascaded amplifier increased as more signal fiber-elements were cascaded. The gain at longer wavelengths also increased significantly as more signal fiber-elements were combined. A gain of 36dB was observed over a bandwidth of >20nm with a gain flatness of ±1dB when three signal fiber elements (S4-S1-S2) were cascaded.

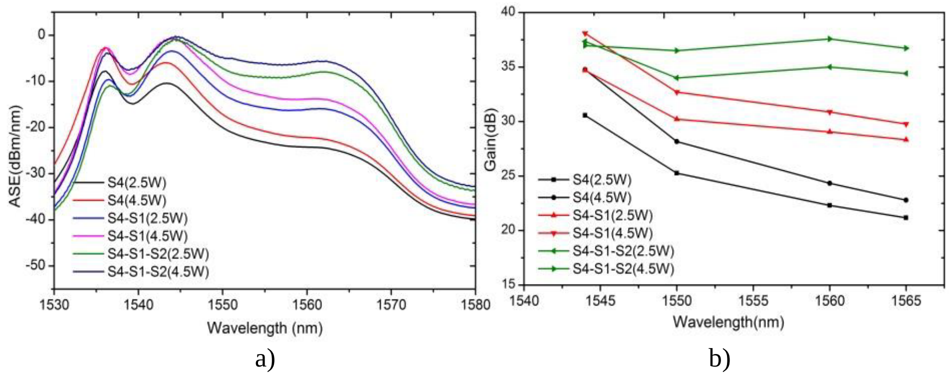



**Fig. 7** Change in a) ASE, and b) gain for different cascaded amplifier configurations at input signal of -23dBm

We have also looked at the performance of ME-EYDFA in WDM test-beds. A source comprising 28 intensity modulated channels in the wavelength range of 1535-1562nm was used instead of the TLS in fig. 5. Fig. 8a), b), and c) show the gain and NF plots for three different cascade configurations of signal fibers: S2, S2-S4, and S2-S4-S1 respectively, at input signal powers of -6.6dBm and 0dBm, and a launched pump power of 6.4W. The gain increment at longer wavelengths can be clearly seen going from Fig 8a) to c). Fig. 8d) shows the amplified signal spectra for S2, S2-S4 and S2-S4-S1 at an input signal power of -6.6 dBm.

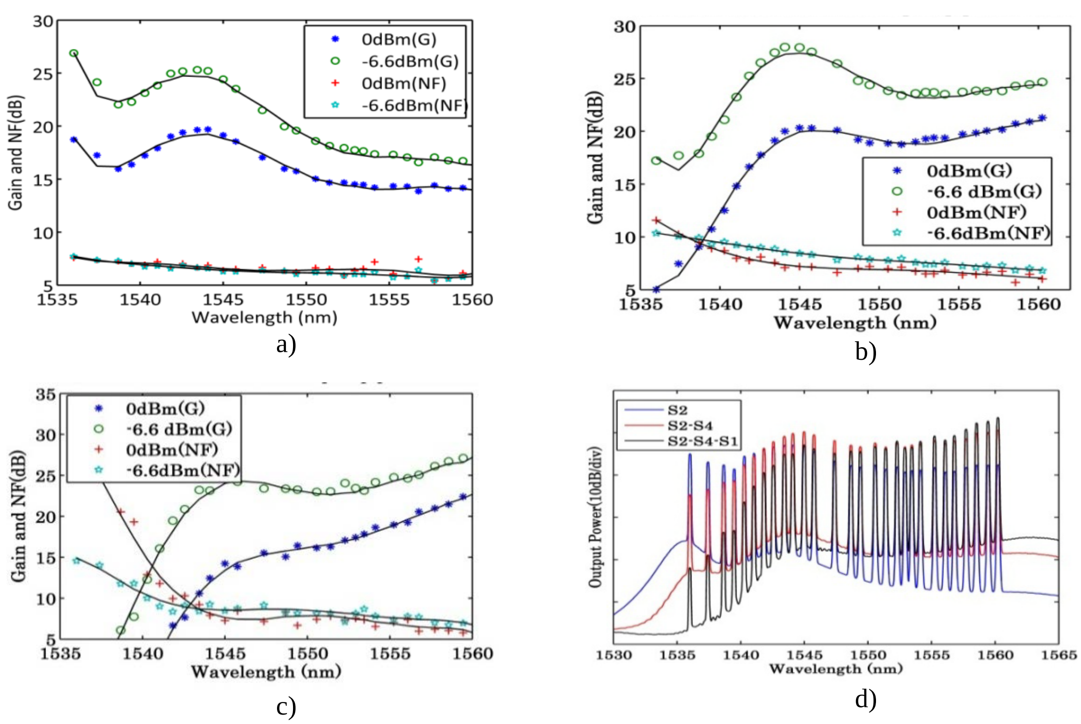
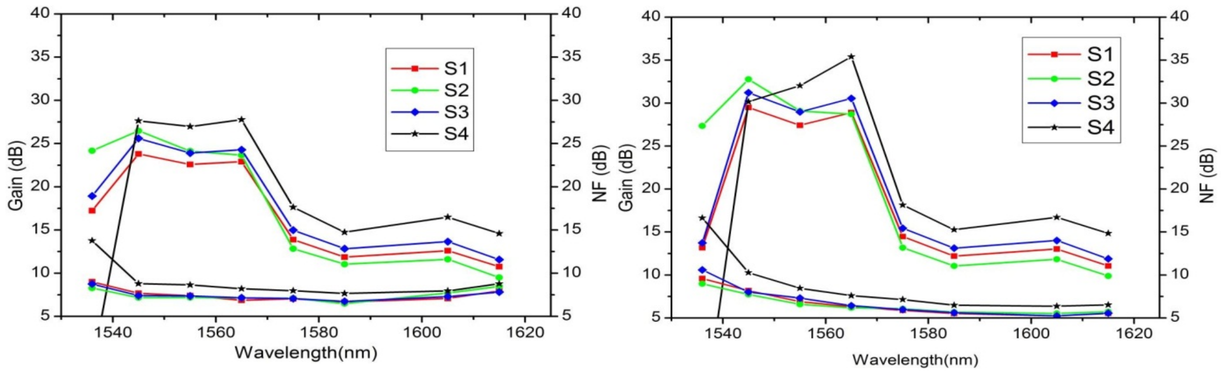



**Fig. 8** Gain and NF performance of cascade combinations; a) S2, b) S2-S4, c) S2-S4-S1, and d) output spectra corresponding to three cascading cases. (The dots in fig. 8a) to 8c) represent the experimental data).

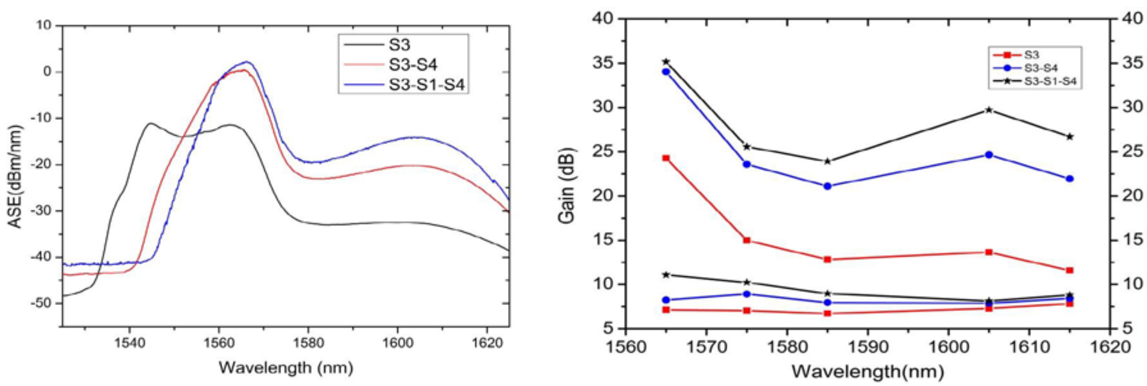
The crosstalk free operation and performance of both MEF and ME-EYDFA was again verified by emulating a SDM based transmission system operating in the C-band[23].




a) b)

**Fig. 9**. Gain and noise figure characterization for signal fibers at input signals of a) -10dBm and b) -23dBm and pump power of 6.4W.

Subsequently the cladding-pumped Er/Yb-doped-MEF was utilized to demonstrate a wideband amplifier, covering both C and L bands. A 9m length of 5-MEF was chosen such that the lowest absorption fiber element (S2), provided a high gain at a wavelength of 1536nm within C-band. Fig.9 a) and b) show the gain and NF performance of individual signal fibers with a pump power of 6.4W and -10dBm and -23dBm of input signals respectively. Note that, the indexing of fiber-elements is not related to the previous work of C-band amplifier. Gain of 32.8 dB and NF of 8dB were obtained for S2 at a wavelength of 1545nm and -23dBm of input signal.




a) b)

**Fig. 10**. a) ASE, and b) Gain and NF for three cascade configurations: S3, S3-S4, and S3-S1-S4 with pump and input signal powers of 6.4W and -10dBm respectively.

The signal fiber-elements were then cascaded one by one by connecting the output of one fiber-element to the input of next fiber-element, and the change in the ASE and gain was measured at a pump power of 6.4W for the following configurations: a) S3, b) S3-S4, c) S3-S1-S4, as shown in fig. 10. An input signal of -10dBm was used to measure the gain in the L-band (1570 -1615nm). It can be observed from fig. 10 that both ASE and gain increases significantly in the L-band as the number of cascaded signal fiber-elements is increased. The maximum gain of 29.5dB was obtained at a wavelength of 1605nm for an input signal of -10dBm for the S3-S1-S4 cascade. With pump and input signal powers of 6.4W and -10dBm respectively, the gain and NF for S2 in the C-band (1536-1565nm) and S3-S4 cascade in the L-band (1570-1615nm) has been plotted together in fig. 11. It can be seen that >20dB gain has been obtained in the 1536-

1615nm wavelength region, covering C and L band simultaneously. Also, the NF over the whole band is relatively flat (8±0.8)dB. The length of the Er/Yb-doped MEF, pump power and input signal power can be optimized further to reduce the ripple in the gain profile. Cladding-pumped ME-EYDFA can thus operate as a split-band amplifier covering both the C-band and the L-band.

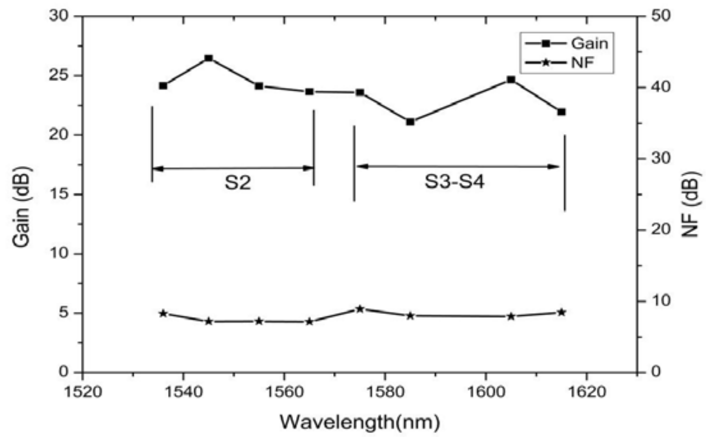



**Fig. 11** Gain and NF for ME-EYDFA (S2 in C-band and S3-S4 cascade in L-band) for 6.4W of pump power and input signal of -10dBm.

## 4 Conclusions

We have presented a novel approach to SDM systems based on multi-element fiber that can offer a crosstalk-free operation and does not require any special additional multiplexing components. MEF technology has been implemented to demonstrate both passive transmission fibers and active fibers for amplifiers. A 9.5 km length of passive Ge-doped 3-MEF was characterized in transmission system, demonstrating the potential of the MEF approach for cross-talk free operation in SDM systems. Also, a cladding-pump 5-MEF was demonstrated, which shares a multimode pump for simultaneous amplification of 4 independent Er/Yb-doped fiber-elements. A maximum gain of 37±2 dB per fiber-element was obtained in the C-band for 10W of launched pump power at a wavelength of 960nm and input signal of -23dBm. Also, the active fiber-elements were cascaded to demonstrate the MEF based C+L split band amplifier with a gain of >20dB covering the wavelength span of 1536nm-1615nm (80nm).

## 5 Acknowledgements

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