

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                              |                                       |                                                | Form Approved OMB No. 0704-0188                                |                                                                        |
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| <b>1. REPORT DATE (DD-MM-YYYY)</b><br>29-05-2009                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                              | <b>2. REPORT TYPE</b><br>Final Report |                                                | <b>3. DATES COVERED (From – To)</b><br>2 July 2008 - 22-Jul-10 |                                                                        |
| <b>4. TITLE AND SUBTITLE</b><br><br>Erbium-doped Photonic Crystal Fiber                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                              |                                       | <b>5a. CONTRACT NUMBER</b><br>FA8655-08-M-4007 |                                                                |                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                              |                                       | <b>5b. GRANT NUMBER</b>                        |                                                                |                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                              |                                       | <b>5c. PROGRAM ELEMENT NUMBER</b>              |                                                                |                                                                        |
| <b>6. AUTHOR(S)</b><br><br>Dr. Kim P Hansen                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                              |                                       | <b>5d. PROJECT NUMBER</b>                      |                                                                |                                                                        |
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|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                              |                                       | <b>5e. WORK UNIT NUMBER</b>                    |                                                                |                                                                        |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b><br>Crystal Fibre A/S<br>Blokken 84<br>Birkerød 3460<br>Denmark                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                              |                                       |                                                | <b>8. PERFORMING ORGANIZATION REPORT NUMBER</b><br><br>N/A     |                                                                        |
| <b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b><br><br>EOARD<br>Unit 4515 BOX 14<br>APO AE 09421                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                              |                                       |                                                | <b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>                        |                                                                        |
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| <b>13. SUPPLEMENTARY NOTES</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                              |                                       |                                                |                                                                |                                                                        |
| <b>14. ABSTRACT</b><br>This report results from a contract tasking Crystal Fibre A/S as follows: '<br>TASK 1: Crystal Fibre will conduct research and development of large mode area, dual clad Er-doped photonic crystal fiber with the design and specifications to be provided by the HQ USAFA/DFP. The intention is to do one fiber type in both a passive and active (Er-doped) version – totally 2 (two) fibers, with up to three samples for each. The fiber is intended to be a tuned cladding design where smaller cores in the cladding region are designed to resonantly couple to higher order modes in the central active core, thereby improving beam quality. The fiber is designed to be polarization maintaining (PM). Nominal fiber designs will include a 19 cell core with nominal specifications of 300 micron 0.6 NA pump core, and signal core diameter to be defined. Crystal Fibre shall fabricate one preform and draw fiber for both the active and passive fiber. Samples may be sent to HQ USAFA/DFP for further testing and characterization.<br>TASK 2: Crystal Fibre shall provide characteristics of the fiber fabricated to include core and cladding diameters, core and cladding numerical apertures, erbium doping concentration, and pump absorption at 1535nm.<br>TASK 3: Crystal Fibre A/S will pay customs and duties associated with shipment of any samples or reports delivered to the HQ USAFA/DFP up to an amount of 500 USD for each of up to six shipments. |                              |                                       |                                                |                                                                |                                                                        |
| <b>15. SUBJECT TERMS</b><br>EOARD, Lasers, optical materials, Optical fiber systems                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                              |                                       |                                                |                                                                |                                                                        |
| <b>16. SECURITY CLASSIFICATION OF:</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                              |                                       | <b>17. LIMITATION OF ABSTRACT</b><br>UL        | <b>18. NUMBER OF PAGES</b><br><br>7                            | <b>19a. NAME OF RESPONSIBLE PERSON</b><br>A. GAVRIELIDES               |
| <b>a. REPORT</b><br>UNCLAS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | <b>b. ABSTRACT</b><br>UNCLAS | <b>c. THIS PAGE</b><br>UNCLAS         |                                                |                                                                | <b>19b. TELEPHONE NUMBER</b> (Include area code)<br>+44 (0)1895 616205 |

## FINAL REPORT - FA8655-08-M-4007 - ITEM 0002

|                        |                                                                                                                                  |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Date:                  | 27 May 2009                                                                                                                      |
| Customer organization: | United States Air Force Academy (USA-FA/DFP)                                                                                     |
| Customer contact:      | Maj. Benjamin G Ward                                                                                                             |
| Contract No.           | FA8655-08-M-4007                                                                                                                 |
| Item                   | 0002                                                                                                                             |
| Project title:         | Erbium-doped Photonic Crystal Fiber                                                                                              |
| Project Manager:       | Kim P. Hansen (kph@crystal-fibre.com)                                                                                            |
| Measurements by:       | Stig Nissen Knudsen and Laurent J. G. Fillon                                                                                     |
| Fiber IDs:             | 080809-01-CF1265, length: 25m<br>080809-02-CF1265, length: 20m<br>080809-04-CF1265, length: 20m<br>090507-04-CF1470, length: 70m |

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The project comprises two sets of fiber with similar design. The first fiber batch is passive (i.e. with pure silica cores without rare earth dopants). These passive fibers act as pilot fibers to test the design and their performance is used to lock the design of the second and final fiber set where the core is doped with Erbium.

### Passive pilot fibers

#### PHYSICAL PROPERTIES:

##### MATERIAL

|                    | FIBER                                    | TARGET |
|--------------------|------------------------------------------|--------|
| Core material:     | Pure silica                              |        |
| Cladding material: | Pure silica and B-doped silica           |        |
| Coating material:  | High temperature acrylate (single layer) |        |

##### DIMENSIONS

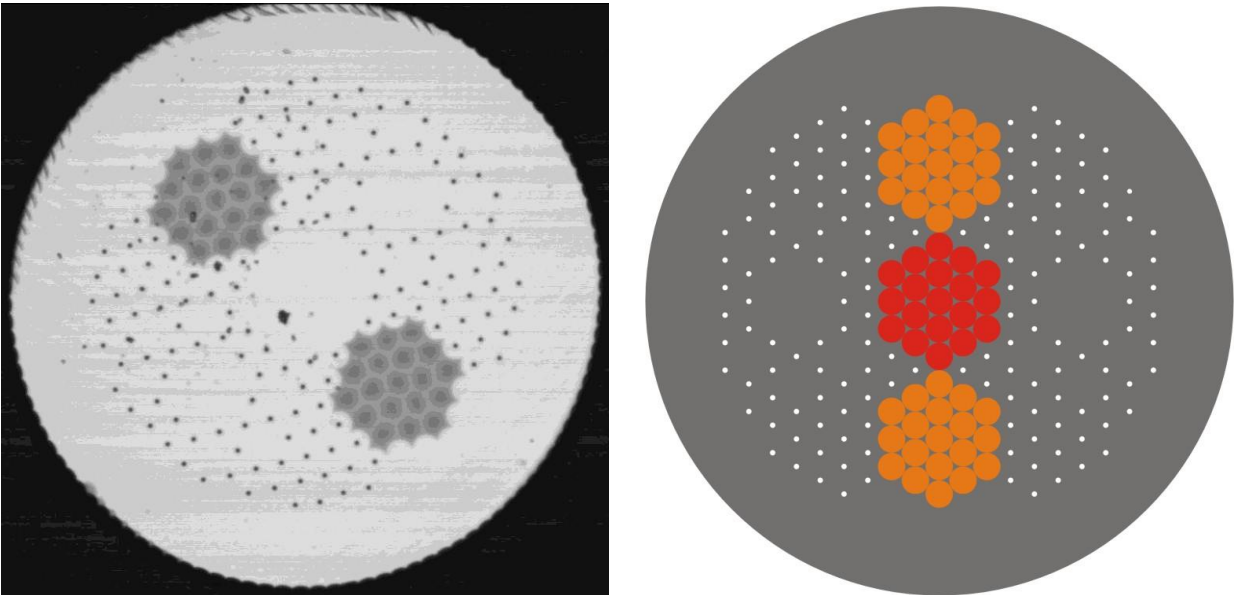
|                                                    | FIBER                                                                       | TARGET                  |
|----------------------------------------------------|-----------------------------------------------------------------------------|-------------------------|
| Inner cladding (pump core) diameter <sup>1</sup> : | 311 $\mu\text{m}$                                                           | 300 $\mu\text{m}$       |
| Cladding diameter:                                 | 695 $\mu\text{m}$                                                           | 650 $\mu\text{m}$       |
| Coating diameter:                                  | 750 $\mu\text{m}$                                                           | 750 $\mu\text{m}$       |
| Pitch:                                             | 14 $\mu\text{m}$                                                            | 14 $\mu\text{m}$        |
| Relative hole size:                                | 080809-01-CF1265: 0,125<br>080809-02-CF1265: 0,14<br>080809-04-CF1265: 0,15 | ~0,13<br>~0,14<br>~0,15 |

| OPTICAL PROPERTIES:                        | FIBER    | TARGET |
|--------------------------------------------|----------|--------|
| SIGNAL CORE:                               |          |        |
| Attenuation @ 1550 nm                      | 25 dB/km | -      |
| MULTIMODE PUMP CORE:                       |          |        |
| Numerical aperture @ 975 nm <sup>2</sup> : | 0.5      | >0.45  |

<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.  
<sup>2</sup>: Measured as the angle corresponding to FWHM of the maximum intensity.

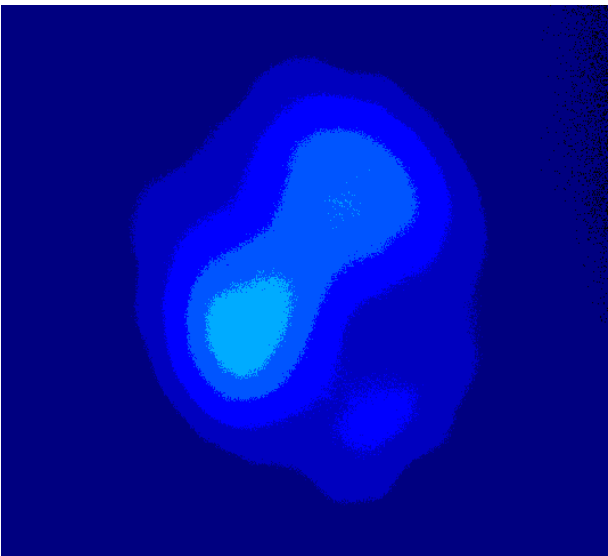
FIBER STRUCTURE

The fiber is a passive pure silica pilot fiber, the purpose of which is to determine structural uniformity and possible fabrication issues of the final Erbium doped fiber. The fiber design is successfully reproduced in the pilot fiber and we have observed no structural nonuniformities or fabrication issues. We were, therefore, confident that the final Erbium doped fiber design could be produced with a high degree of precision.



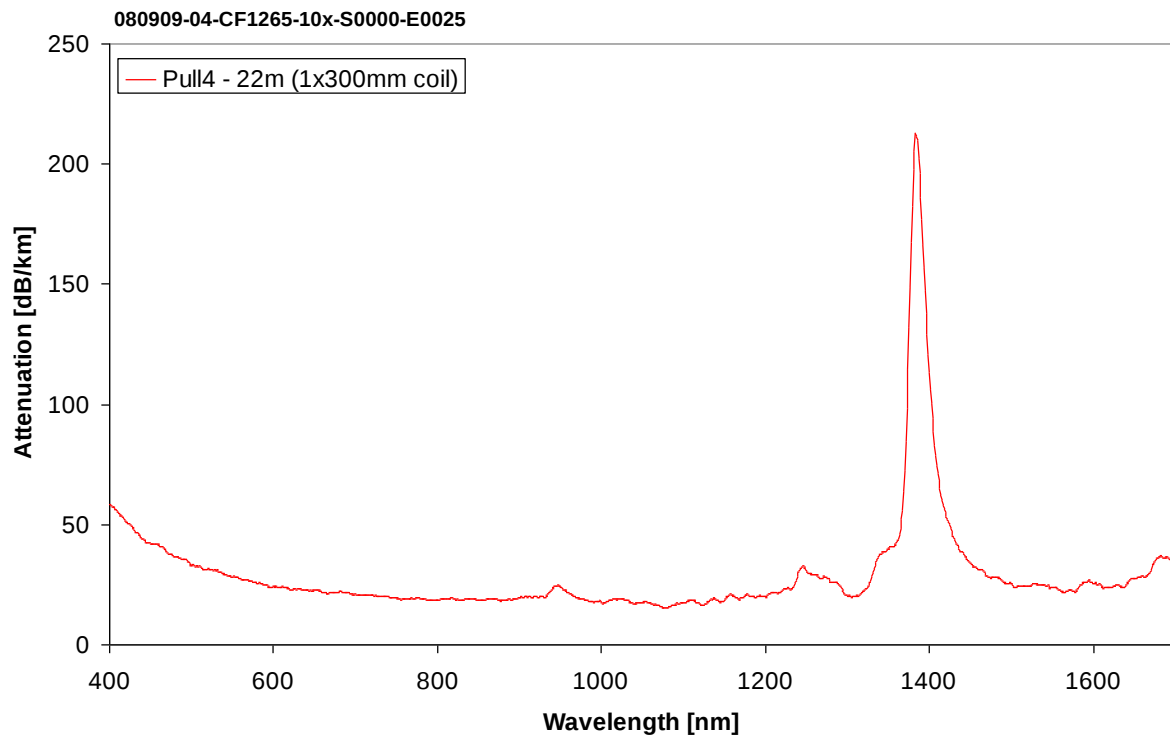
Left: Optical microscope picture of the fiber cross section inside the airclad. Right: Sketch of the design target as specified by USAFA.

NEAR FIELD



Near field of o8o8o9-o4-CF1265 recorded at 1550 nm. 1550 nm light launched into core by 10x aspheric lens. Central core appears highly multi-moded. We have not controlled axis of polarized light coupled to fiber with respect to stress rods – it is "random". Bending the fiber was "random" with respect to the stress rod axis. Above picture is for 2 m of almost straight fiber. Transmitted 1550 nm light is loss very quickly when bending the 2 m sample.

## SPECTRAL ATTENUATION



## Active fibers

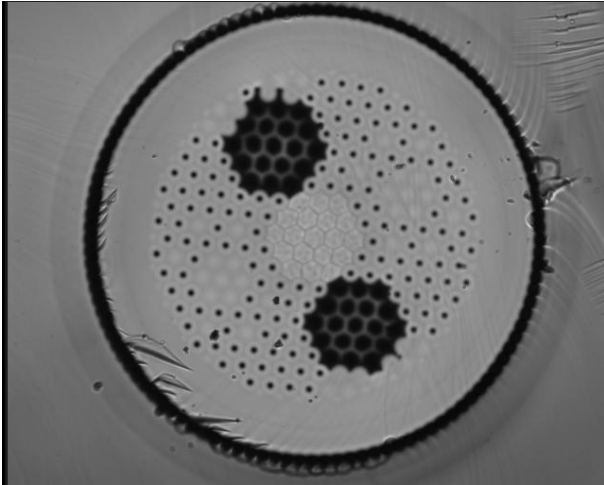
The active fiber batch was produced with targets identical to the passive pilot fibers, which had shown good performance and single-mode operation in the tests at USAFA. The relative hole-size sweep used in the pilot fiber drawing was replaced with a fixed target of 0.14.

| PHYSICAL PROPERTIES:                               | FIBER                                    | TARGET    |
|----------------------------------------------------|------------------------------------------|-----------|
| MATERIAL                                           |                                          |           |
| Core material:                                     | Er/Al doped silica                       |           |
| Cladding material:                                 | Pure silica and B-doped silica           |           |
| Coating material:                                  | High temperature acrylate (single layer) |           |
| DIMENSIONS                                         |                                          |           |
| Inner cladding (pump core) diameter <sup>1</sup> : | 310 μm                                   | 300 μm    |
| Cladding diameter:                                 | 705 μm                                   | 650 μm    |
| Coating diameter:                                  | 760 μm                                   | 750 μm    |
| Pitch:                                             | 13,6 μm                                  | 14 μm     |
| Relative hole size:                                | 0,14-0.15                                | 0.14      |
| OPTICAL PROPERTIES:                                | FIBER                                    | TARGET    |
| MULTIMODE PUMP CORE:                               |                                          |           |
| Numerical aperture @ 975 nm <sup>2</sup> :         | 0.54                                     | >0.45     |
| Pump absorption @ 1530 nm:                         | 1.2 dB/m                                 | >0.5 dB/m |

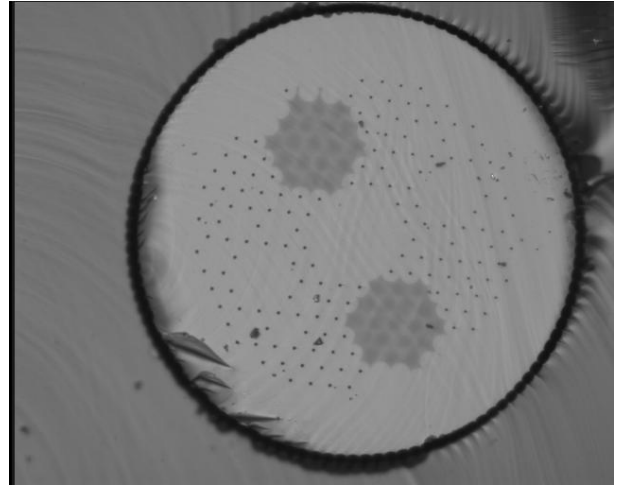
<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.

<sup>2</sup>: Measured as the angle corresponding to FWHM of the maximum intensity.

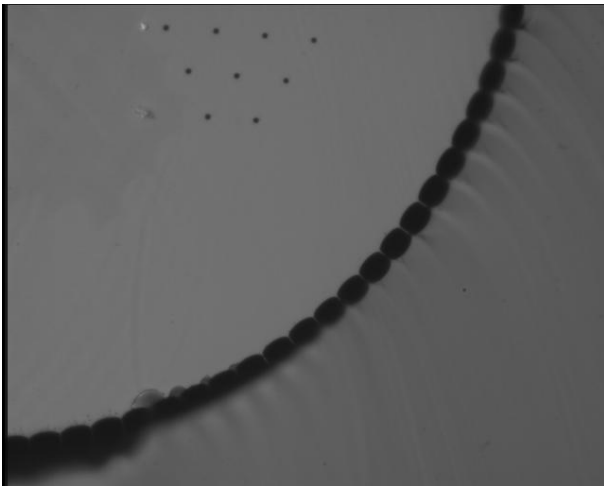
## FIBER STRUCTURE



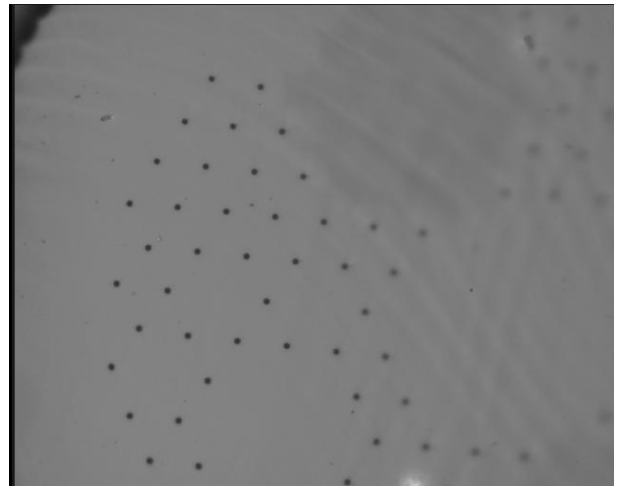
090507-2-CF1470 start x 20 bk ill.tif



090507-2-CF1470 start x 20 tp ill.tif



090507-2-CF1470 start x 50 tp bro ill.tif



090507-2-CF1470 start x 50 tp ill.tif

**Top left:** Optical microscope picture of the fiber cross section using illumination from the back to reveal index differences.

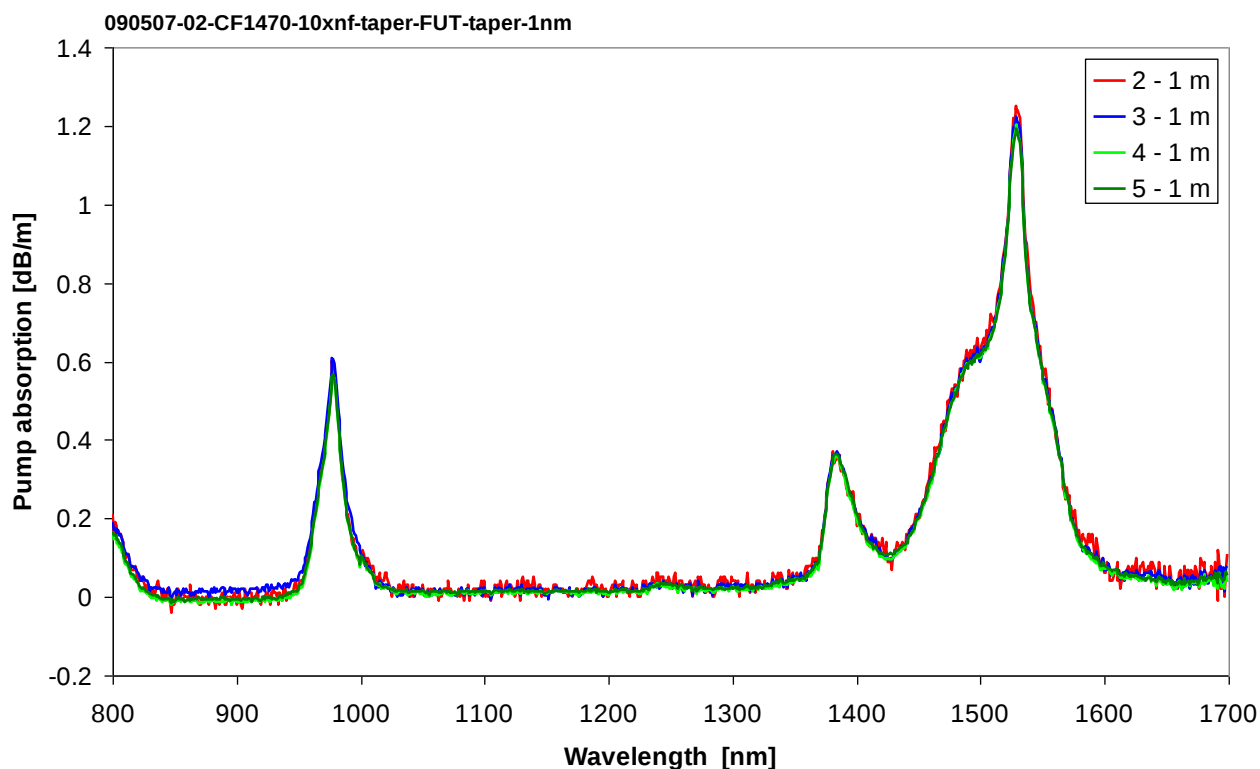
**Top right:** As top left but with front illumination

**Bottom left:** Optical microscope picture of part of the airclad with front illumination

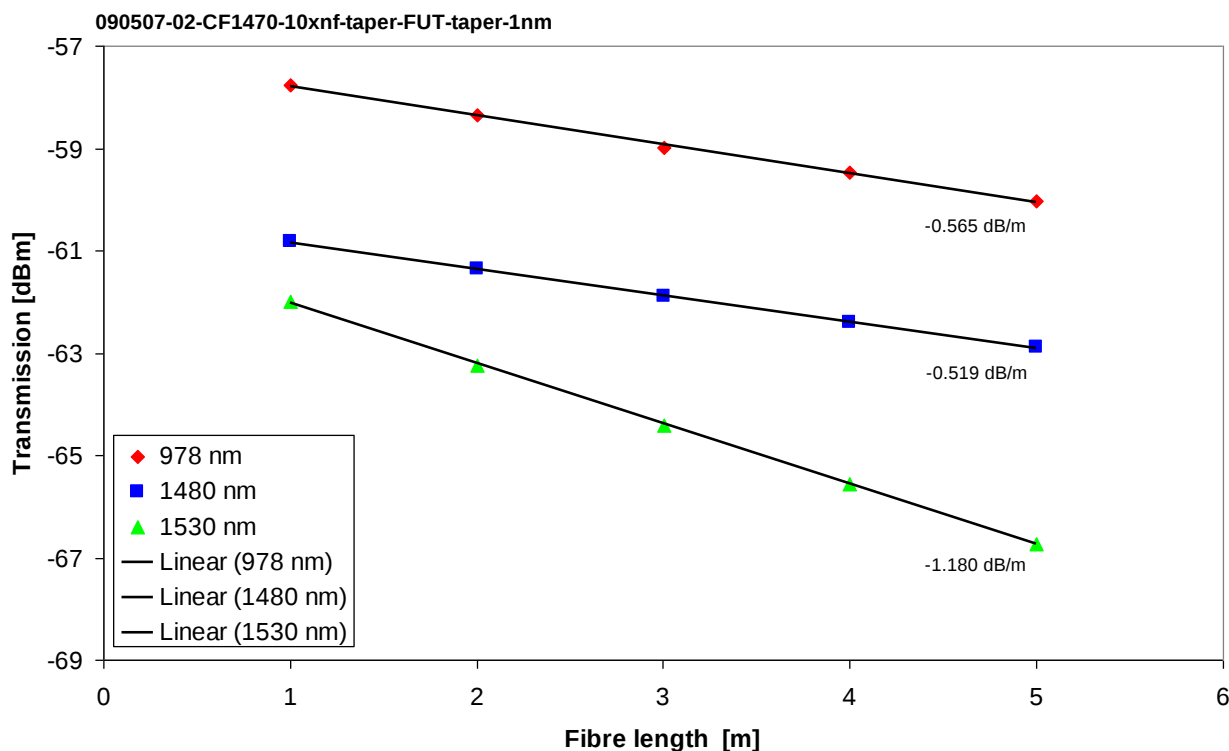
**Bottom right:** Zoom on the structure inside the airclad.

## PUMP ABSORPTION

The pump absorption of the fiber is measured by cut-back using a broadband light source (see spectral attenuation plots below).



The transmission as function of length is plotted in the figure below for the wavelengths 978 nm, 1480 nm and 1530 nm. The success criterion was to reach a minimum of 0.5 dB/m pump absorption at 1530 nm and 1.18 dB/m was measured.



Measurements completed 20.05.2008. All target parameters are concluded to be within specifications.

A handwritten signature in blue ink, appearing to be 'KPH', with a long horizontal stroke extending to the right.

Kim P. Hansen