Fiber coupled pumping concepts for double-clad fibers

Outline

- Introduction
- Notch coupling
- Side-coupling
- End-coupling
- Examples
- Reliability
- Conclusion

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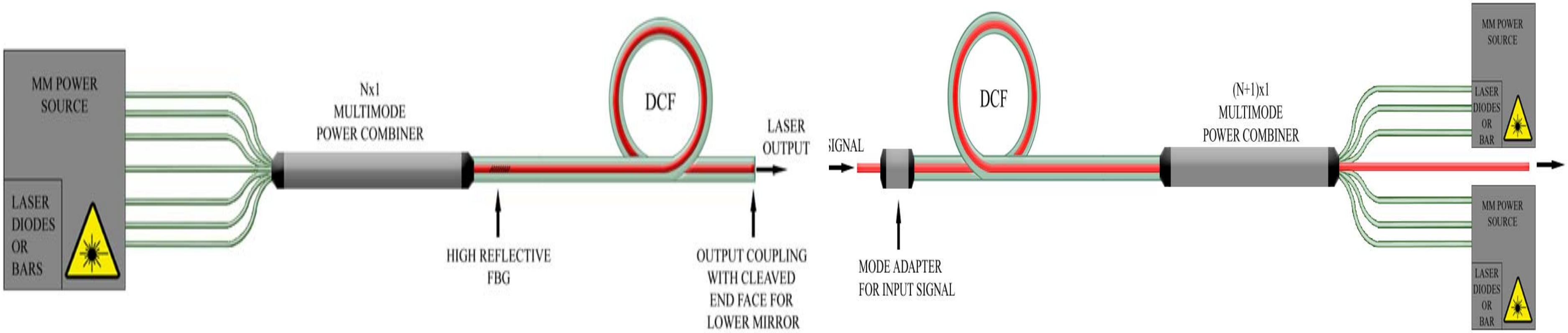
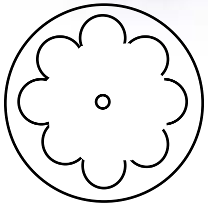
Double-Clad Fiber Lasers and Amplifiers

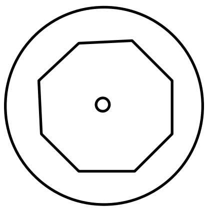


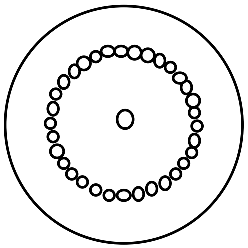
- **Double-clad fiber enables greater amounts of pump power to be coupled into the fiber**
  - Spatial multiplexing
  - Multimode pump diodes can be used
  - Laser diode bars can be used
  - Fiber pigtailed pumps bring more flexibility to the laser
    - **Separate optical fiber engine from pump module**
- **Larger fiber cores can be used because of larger fiber diameter**
  - Reduce non-linear effects
  - More power can be extracted thus more power at the output
    - **kW CW fiber laser and Multi-kW pulsed fiber laser**

Double-Clad fibers

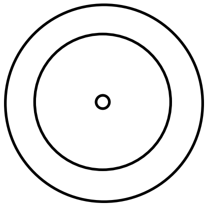
- **3 types of secondary claddings**
  - **Fluorine-doped silica secondary cladding**
    - **Numerical aperture 0.22 to 0.3**
    - **limited coupling efficiency**
  - **Fluoro-acrylate doped secondary cladding**
    - **Numerical aperture 0.46**
    - **Cladding easily removed, most used DCF type**
  - **All-glass Air-Clad DCF**
    - **Numerical aperture 0.6**
    - **Difficult to handle**







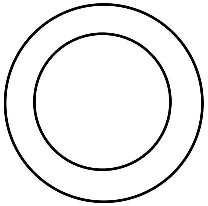
- **Secondary cladding are non-circular shaped to increase mode mixing and absorption**
- **Relay DCF is usually circular**



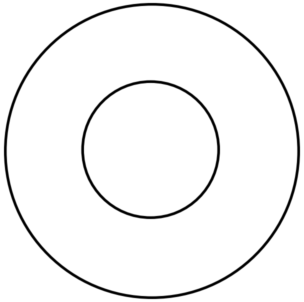
- **Standard secondary cladding diameters**
  - **125 µm, 200 µm, 250 µm and 400 µm**

Multimode pump fibers

- **Fluorine-doped silica cladding**
  - Numerical aperture : 0.12, 0.15, 0.22
- **Core/Cladding diameters**
  - 100 µm/ 125 µm
  - 105 µm/ 125 µm
  - 200 µm/220 µm
  - 400 µm/440µm



- **Fluoro-acrylate doped cladding**
  - Numerical aperture : 0.46
  - 125 µm core



- **Pumps**
  - Single-emitter pump into 105 µm core fibers
  - Laser diode bars Into 105 µm, 200 and 400 µm core fibers

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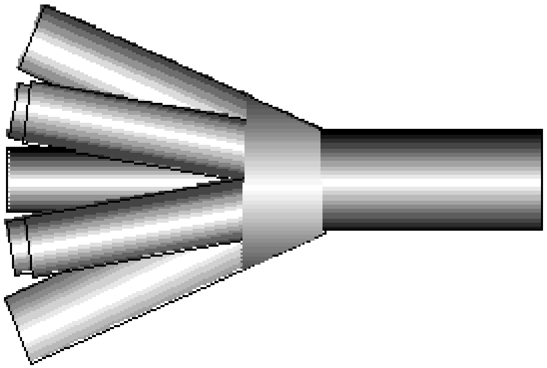
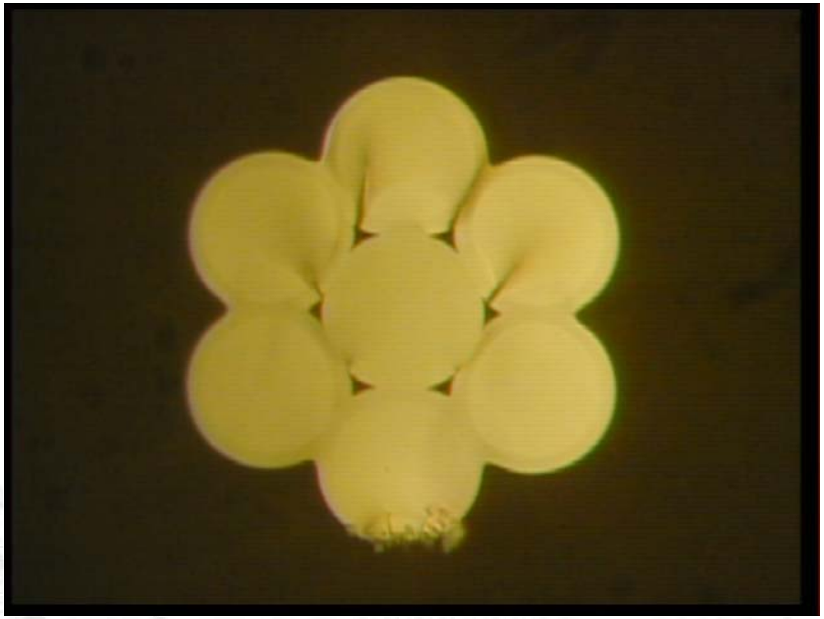
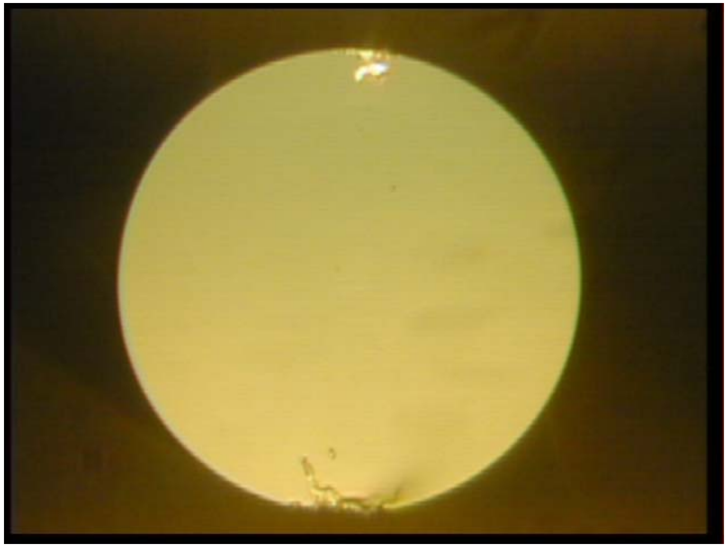
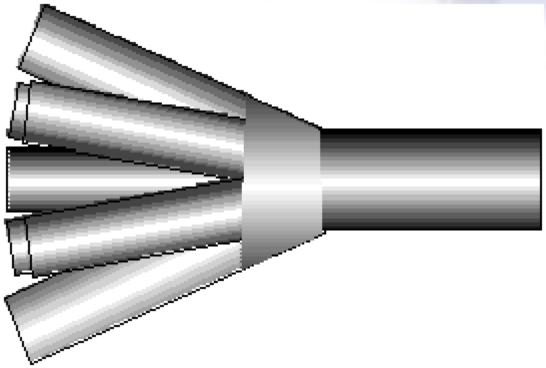
fiber bundle and output fiber







Tapered fiber bundle and brightness conservation



Design rule: Brightness conservation

In a fiber $NA = n_{co} \sin \theta_c$

- n_{co} is the index of refraction of the core
- And θ_c is the critical angle

For a ray in a tapered multimode fiber

$$\phi_i \sin \theta_i = \phi_o \sin \theta_o$$

- ϕ is the diameter of the fiber and θ is the axial angle of the mode

For a bundle, low loss is achieved when

$$\phi_b NA_b \leq \phi_o NA_o$$

- ϕ_b is the diameter of the fiber bundle before tapering,
- NA_b is the largest numerical aperture of the input fibers or the numerical aperture filled by the pump lasers,
- ϕ_o is the core diameter of the output fiber and
- NA_o is the numerical aperture of the output fiber.

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N x 1 Multimode fused fiber combiner

Input fibers\ Output fiber	125 µm DCF, NA =0.46	250 µm DCF, NA = 0.46	400 µm DCF, NA =0.46
105 / 125 µm, NA = 0.15	7 x 1	19 x 1	61 x 1
105 / 125 µm, NA = 0.22	4 x 1	7 x 1	37 x 1
200 / 220 µm, NA = 0.22	1 x 1	4 x 1	7 x 1
400 / 440 µm, NA = 0.22	N/A	1 x 1	3 x 1

Assuming fully filled pump fibers

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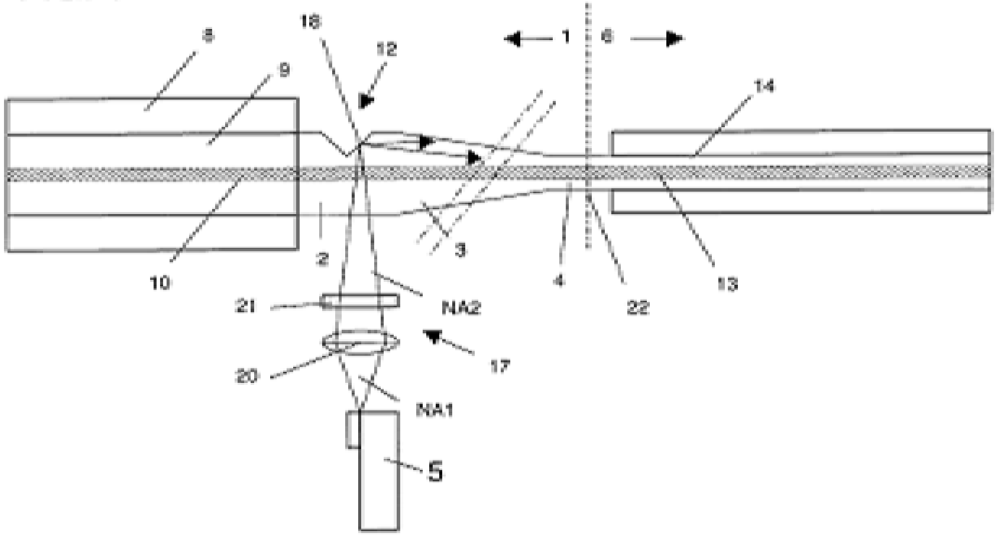
Double clad fiber components for fiber lasers

- Fiber component can replace bulk optic component
  - Monolithic fiber structure
  - Fused component and splices cannot be misaligned
- Different method for coupling pump power into DCF
  - Side coupling
    - Notch coupling (Naval research lab/Keopsys)
    - Angle coupling
    - Fused taper side coupling (IPG)
    - Fused coupler side coupling (JDSU)
    - Co-linear coupling (GT-WAVE, SPI)
  - End pumping
    - Tapered bundle end pumping with signal feed-through (OFS, JDSU)
    - Large core fiber end pumping (ITF)
  - Disclaimer: Technologies presented are based on published patents not necessarily on what the companies are actually using.
- Two parameters
  - Coupling efficiency : Coupled pump power into DCF/initial pump power
  - Brightness efficiency : $(\Sigma(\phi_i^2)) * NA_i^2 / (\phi_o NA_o)^2$

Notch Coupling

FIG. 1



- **US patent #6,731,837, Goldberg et al.**
- **Coupling efficiency 100% if**
  - **beam spot size < notch area and**
  - **$NA_i = NA_o$**
- **Brightness efficiency <25% if $NA_i = NA_o$**

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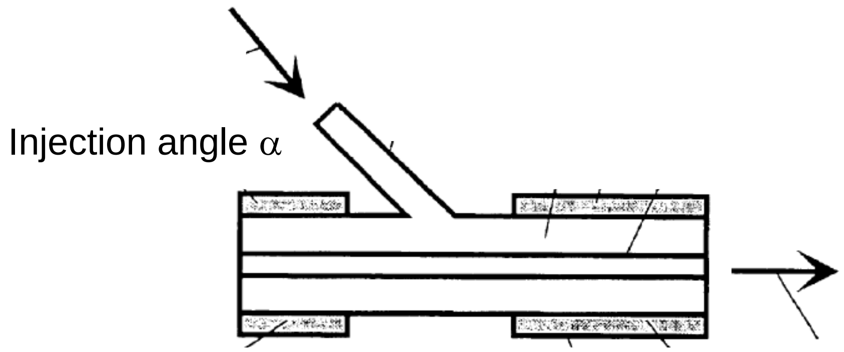
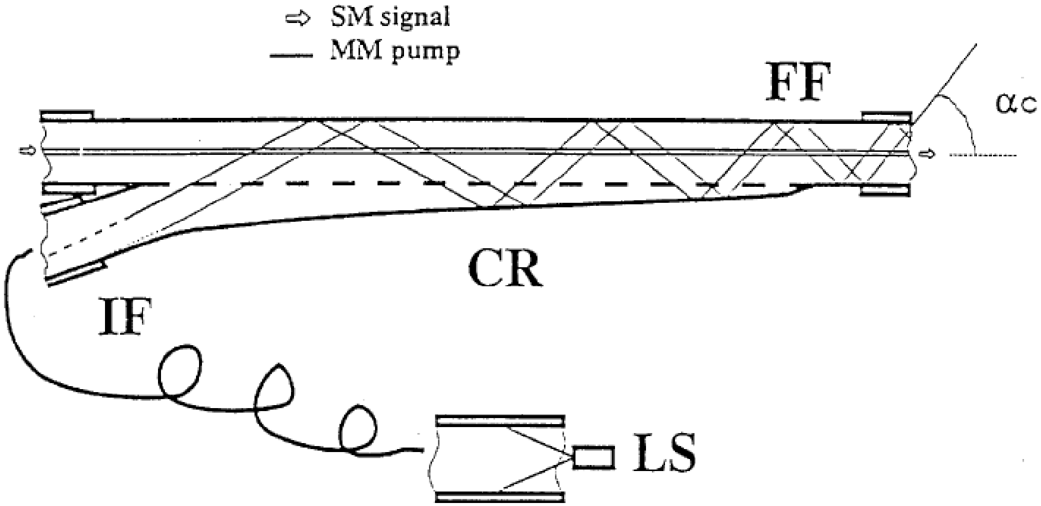
Angle coupling



- **Coupling efficiency 100% if**
  - $NA_i + \alpha < NA_o$
  - $\phi_i < \phi_o$
- **Brightness efficiency**
  - Very poor

Tapered pump fiber side-coupling



- **US patent 5,999,673, Gapontsev et al.**
- **(1+1) x1**

- **Coupling efficiency 100% if**
  - $NA_i < Na_o * \phi_I/(\phi_i + \phi_o)$
  - $\phi_i < \phi_o$
- **Brightness efficiency = $(NA_o/ NA_i * \phi_i/(\phi_i + \phi_o))^2$**

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Fused coupler

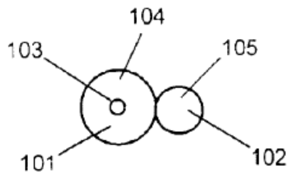


Figure 10

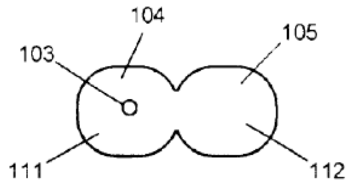
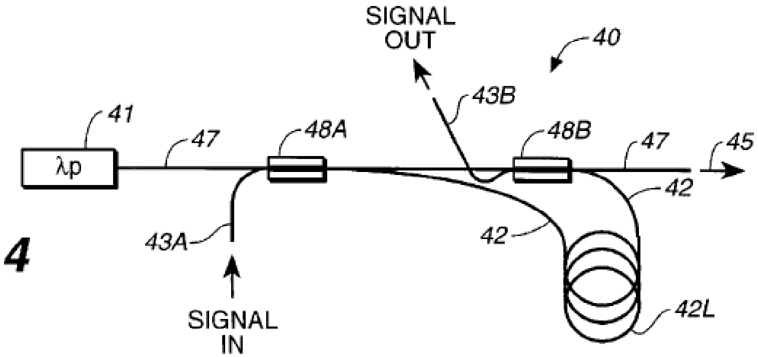


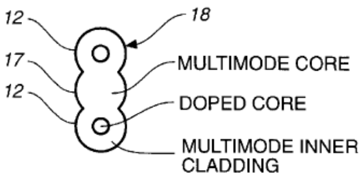
Figure 11

FIG._4



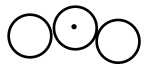
- US patent 6,434,295, MacCormack et al.
- US patent 6,826,335, Grudinin et al.
- (1+1) x (1+1), (1+2) x (1+2)

FIG._1A



- Coupling ratio $(\Sigma \phi_o^2)/ (\Sigma \phi^2)$
- Brightness efficiency = coupling ratio * $(NA_i / NA_o)^2$

GT-wave



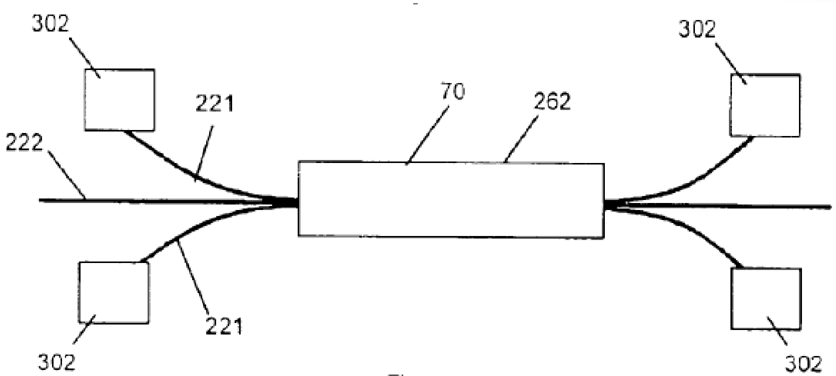


Figure 32

- US patent 6,826,335, Grudinin et al.
- (2+1) x 1 structure
- Coupling efficiency tends to 100%
- Brightness efficiency =1/3 * $(NA_i / NA_o)^2$

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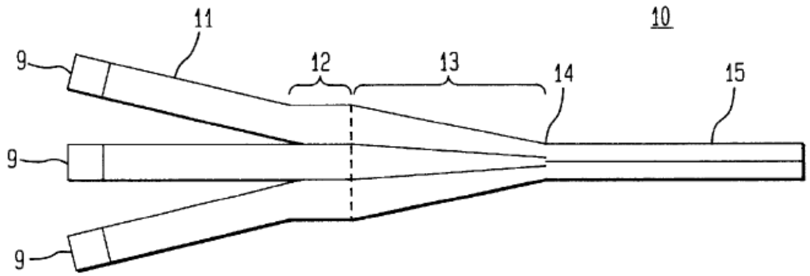
Tapered bundle end pumping with signal feed-through

FIG. 1A



- US patent 5,864,644, DiGiovanni et al.
- US patent 6,434,302, Fidric et Al.
- (6+1) x 1 structure
- Coupling efficiency 100% if
  - $\phi_b \, NA_b \leq \phi_o \, Na_o$
- Brightness efficiency = 6/7 * $(\phi_b \, NA_b \, / \, \phi_o \, Na_o)^2$

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Large core fiber end pumping

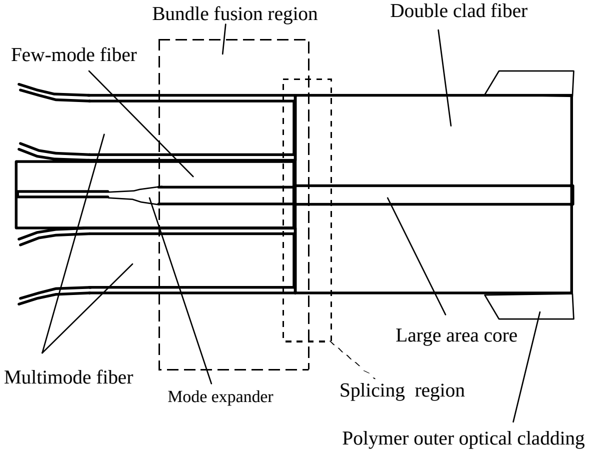

Figure 3

- **US Patent pending, Gonthier et al.**
- **(N+1) x 1, with N = 4 to 12 and more**
- **Coupling efficiency 100% if**
  - $\phi_b \, NA_b \leq \phi_o \, Na_o$
- **Brightness efficiency = N** $(\phi_i^{\,2} \; NA_b \; / \; \phi_o \, Na_o)^2$

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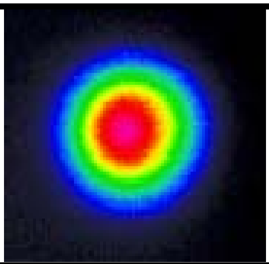
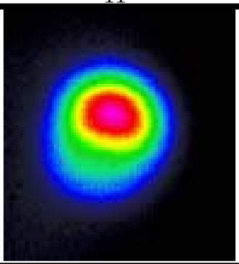
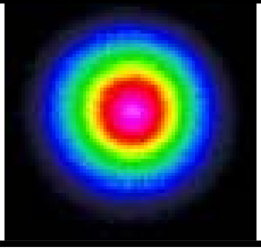
(N+1) x 1 Multimode fused fiber combiner (cont)

Configu -ration	Input pump fibers	Signal fiber	Double-clad fiber	Fundamental mode	Deformation due to LP_{11} mode
(6+1)x1	200/220 µm, NA= 0.22	20/125 µm, NA = 0.06	20/400 µm, NA = 0.06/0.46		
(6+1)x1	105/125 µm, NA= 0.22	20/125 µm, NA = 0.11	20/200 µm, NA = 0.11/0.46		

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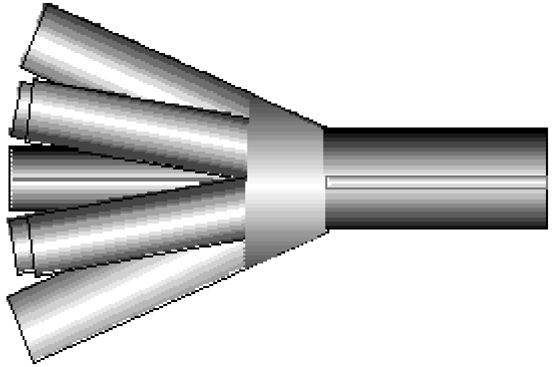
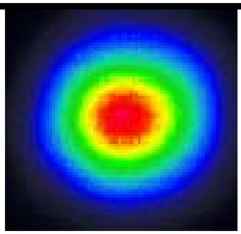
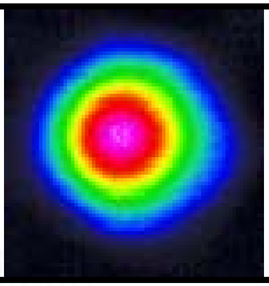
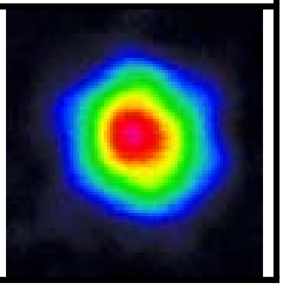
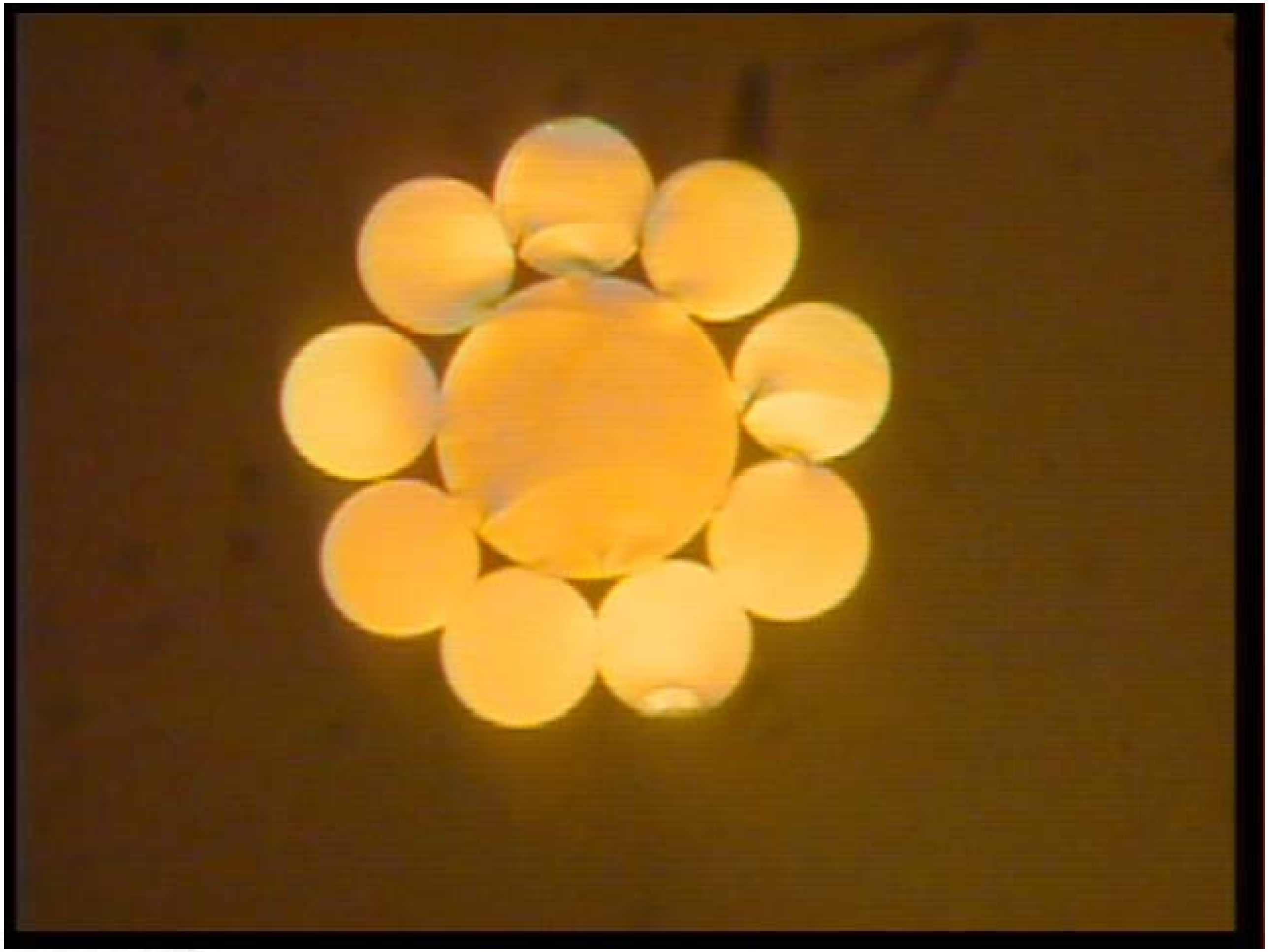
Mode adaptor integrated into (N+1) x 1 combiners



Configu-ration	Pump fiber	Fiber signal	Double-clad fiber	Fundamental mode	Deformation due to waveguide structure
(6+1)x1	105/125 µm, NA = 0.22	Puremode 1060	20/400 0.06		
(6+1)x1	200/220 µm, NA = 0.22	Puremode 1060	20/400 0.06		

(9+1) cleaved fiber bundle



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Coupling into 125 µm DCF

DCF diameter (µm)		125								
Pump parameters										
diameter (µm)		105		105		105		200		400
NA		0.15		0.22		0.22		0.22		0.22
power (W)		5		5.5		30		50		400
	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)
Fused taper *	2	9.5	1	5.2	1	28.5	1	13.1	1	95.0
fused coupler*	4	14.6	1	4.5	1	24.5	1	30.0	1	113.7
Co-linear**,+	14	66.5	8	41.8	8	228.0	2	95.0	2	500.0
Tapered bundle	7	33.3	4	20.9	4	114.0	1	47.5	1	250.0
Tapered bundle w feed-through**	6	28.5	6	22.5	6	122.7	6	51.1	6	102.3
Large core bundle**	6	28.5	4	20.9	4	114.0	4	47.5	4	95.0

* several can be put in series
** two can be used
\+ Double the power, but three times the length

- **Red color indicates coupling schemes to lossy to be of practical use**
- **Fused couplers are less efficient than fused tapers**
- **Bundle with feed-through are less efficient than bundle**
- **Large pump fiber cannot be used if DCF is too small**
- **There is an advantage to use low NA pumps, even if they are less powerful**

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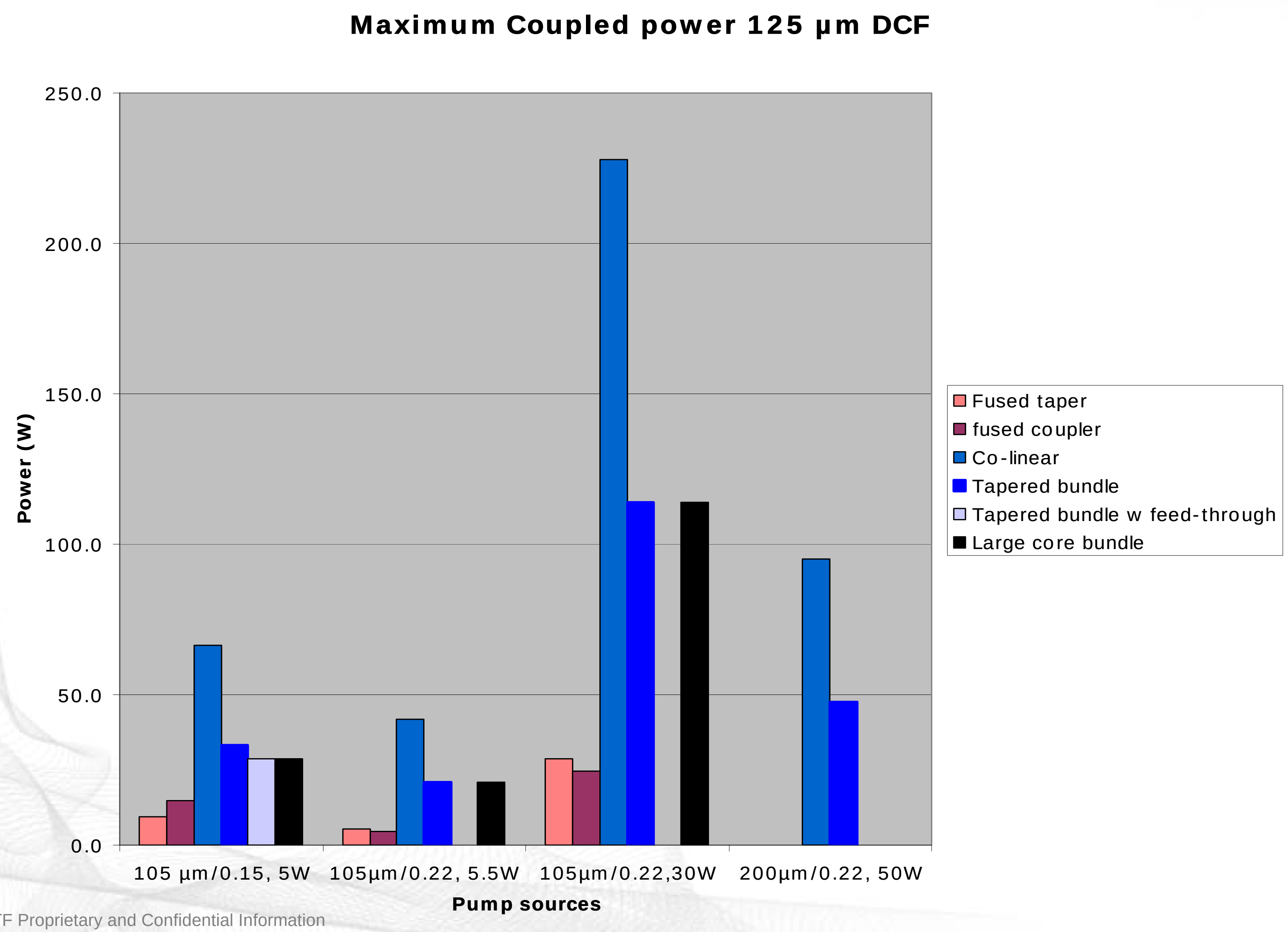
Coupling into 125 µm DCF



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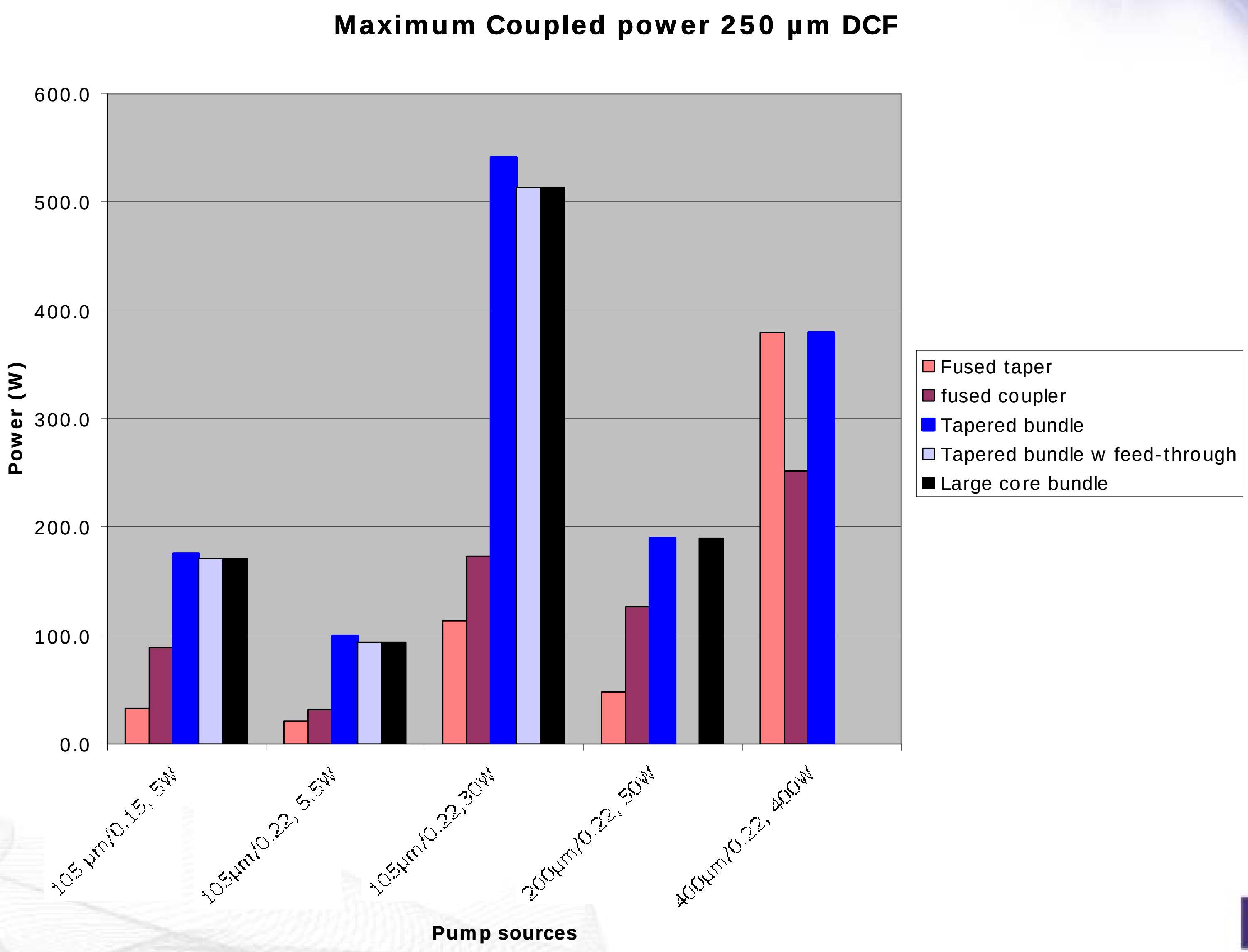
Coupling into 250 µm DCF

DCF diameter (µm)		250								
Pump parameters										
diameter (µm)		105		105		105		200		400
NA		0.15		0.22		0.22		0.22		0.22
power (W)		5		5.5		30		50		400
	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)
Fused taper *	7	33.3	4	20.9	4	114.0	1	47.5	1	380.0
fused coupler*	19	89.6	10	31.8	10	173.2	4	126.1	1	252.3
Co-linear**,+	74	351.5	38	198.6	38	1083.0	8	380.0	2	760.0
Tapered bundle	37	175.8	19	99.3	19	541.5	4	190.0	1	380.0
Tapered bundle w feed-through**	36	171.0	18	94.1	18	513.0	6	142.5	6	570.0
Large core bundle**	36	171.0	18	94.1	18	513.0	4	190.0	4	380.0

* several can be put in series
** two can be used
+ Double the power, but three times the length

- **Orange indicates number of pump fiber to large to be practical**
- **Large increase in pump coupling vs 125 µm DCF**
- **Power advantage of low NA pump reduced but still there but number of pump is too large and will be to expensive**
  - **This makes bar pumping more attractive**

Coupling into 250 µm DCF



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Coupling into 400 µm DCF

DCF diameter (µm)		400								
Pump parameters										
diameter (µm)		105		105		105		200		400
NA		0.15		0.22		0.22		0.22		0.22
power (W)		5		5.5		30		50		400
	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)	# pumps	Power (W)
Fused taper *	19	90.3	7	36.6	7	199.5	4	190.0	1	380.0
fused coupler*	37	175.0	19	99.3	19	541.5	4	162.8	1	325.5
Co-linear**,+	122	579.5	74	386.7	74	2109.0	20	950.0	6	2280.0
Tapered bundle	61	289.8	37	193.3	37	1054.5	10	475.0	3	1140.0
Tapered bundle w feed-through**	60	285.0	36	188.1	36	1026.0	6	285.0	6	570.0
Large core bundle**	60	285.0	36	188.1	36	1026.0	9	427.5	4	1216.0

* several can be put in series
** two can be used
+ Double the power, but three times the length

- **Brown indicates component is too large (1.2 mm fiber)**
- **Kilowatt pumping with possible single component**

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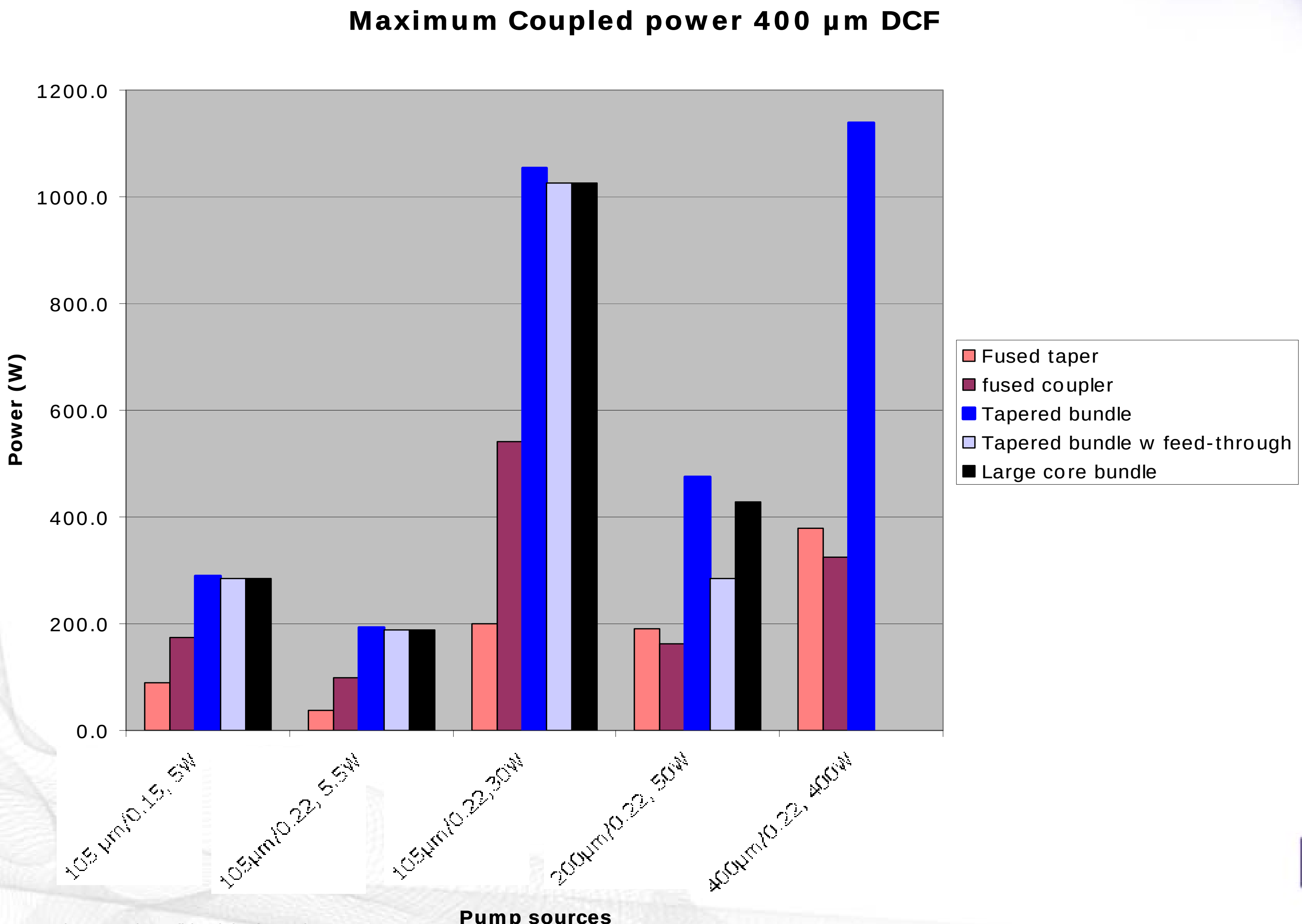
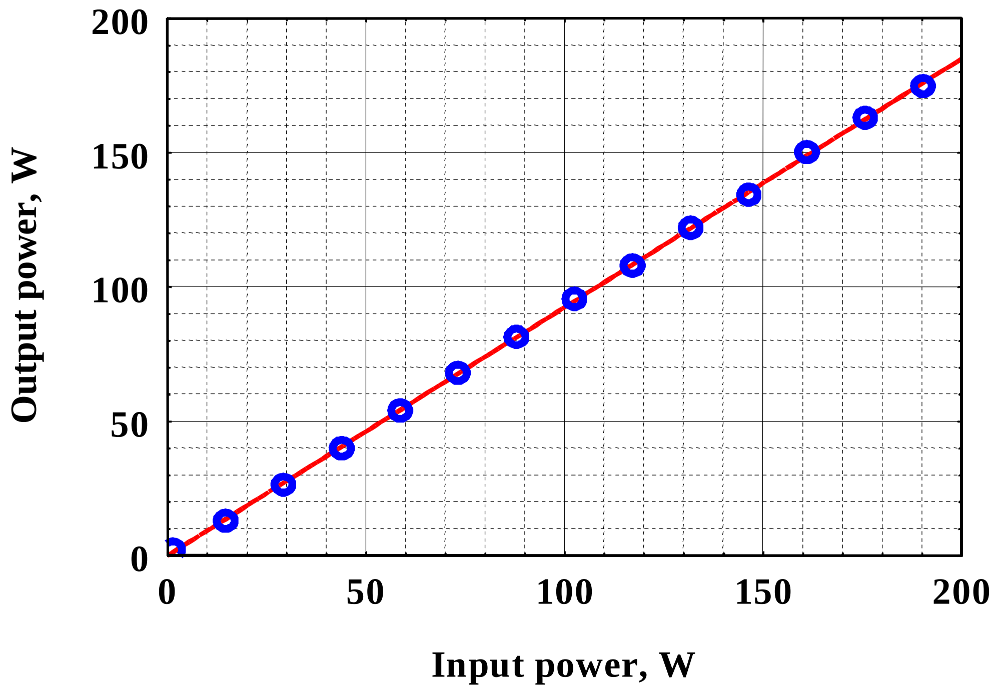
Coupling into 400 µm DCF



Reliability

- **In all-fiber component, reliability depends more on power dissipation capacity then on power handling**
  - Low loss in essential
  - Packaging with good heat dissipation will enable higher power operation
- **Longer term reliability for components**
- **Power handling in laser operation**

High-power test



- **Maximum power achieved was limited by the test source**
- **At 195 W sample shows**
  - No increase in insertion loss
  - No measurable temperature increase of the package (passive heat-sinking)
  - Sample efficiently dissipated 20 W of power
- **With lower loss (<0.1 dB), ITF's All-Fiber® components should handle greater than 700 W.**

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Combiner Reliability: High Power Test at 123W

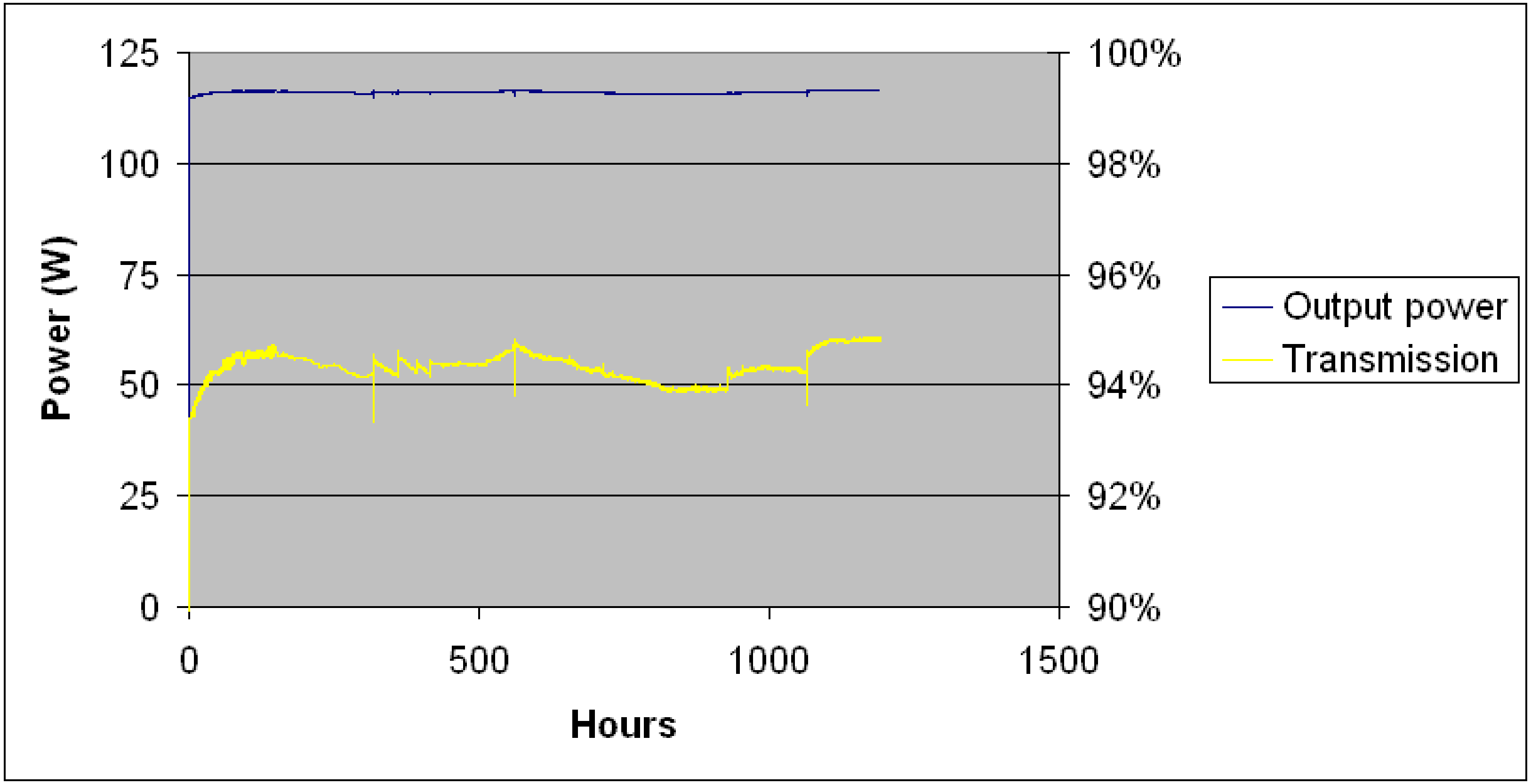

Fig. 11 Output power and Transmission of a Multi-Mode Combiner during a high power test at 123W

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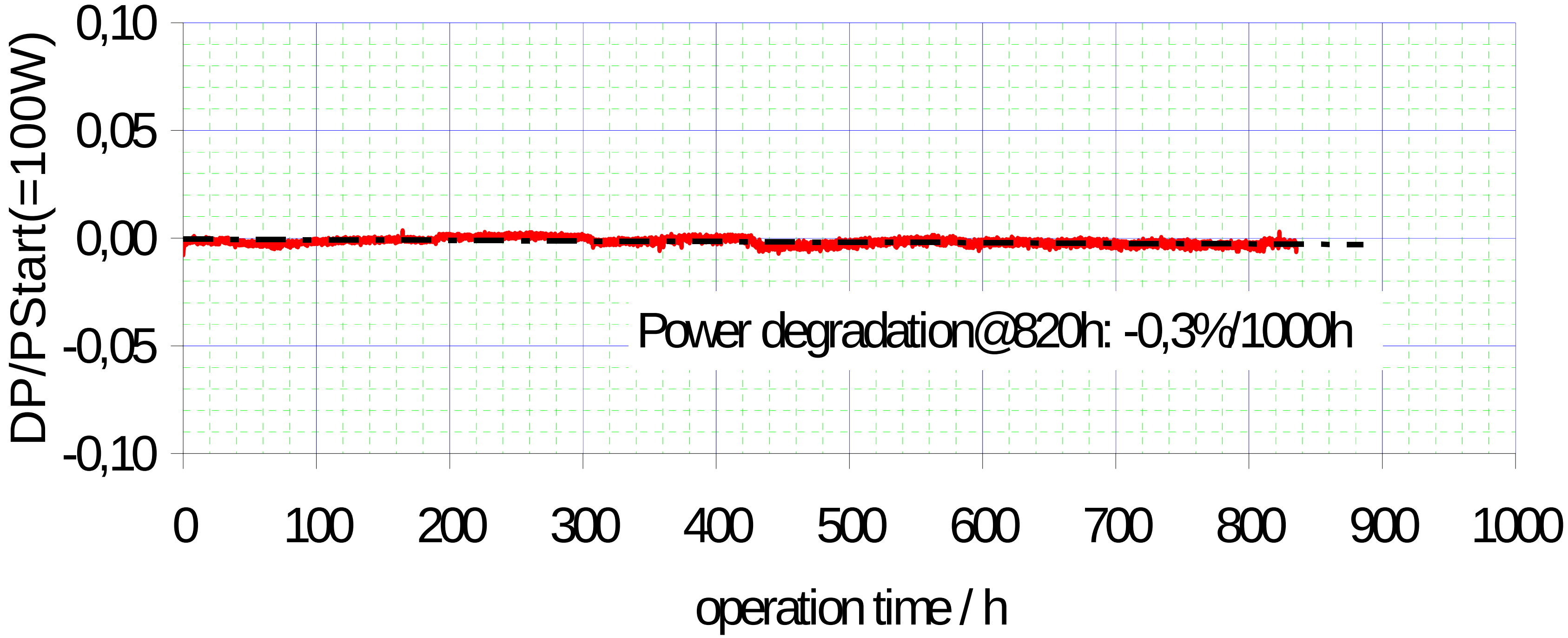
TFBs, latest long time aging test at 100W (Jenoptik, Photonics West 2005)



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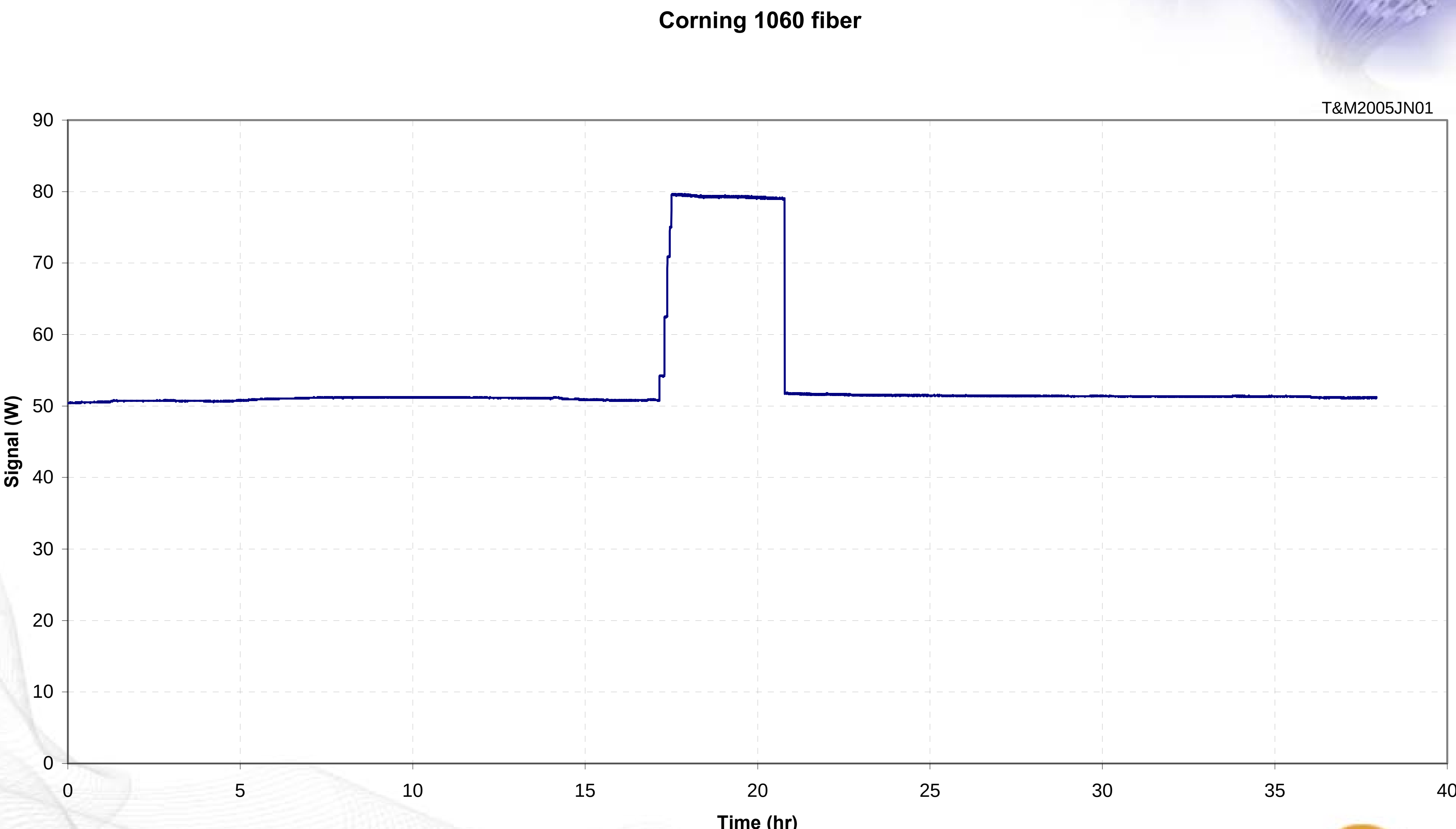
Short term stability test of single mode fiber laser



Conclusion

- **Number of techniques times number of fiber types = Large number of possibilities**
- **However, not all techniques are available on the open market**
  - **Commercially available**
    - **Fiber bundles with or without feed-through**
    - **Side couplers**
- **Amplifier design must take into account other parameter such as gain fiber length to select proper components**
- **High power handling required for multi-100 watt class components**
  - **ITF components can be used in multi-100 watt applications**

In development at ITF

- **High power package for kilowatt class component**
- **Tapered fiber bundles with large core PM fibers**

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