Mid-Infrared Photonics Group
George Green Institute for Electromagnetics Research
Faculty of Engineering

The University of Nottingham

Progress of Round Robin on MIR active fibre modelling

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Politecnico di Bari

DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELL'INFORMAZIONE

Outline

- Test problem
- Method of Single Expression (NPU,NIT,KUT)
- Relaxation Method (PB)
- Relaxation Method (NU, WrUT)
- Summary

Test problem

Test problem

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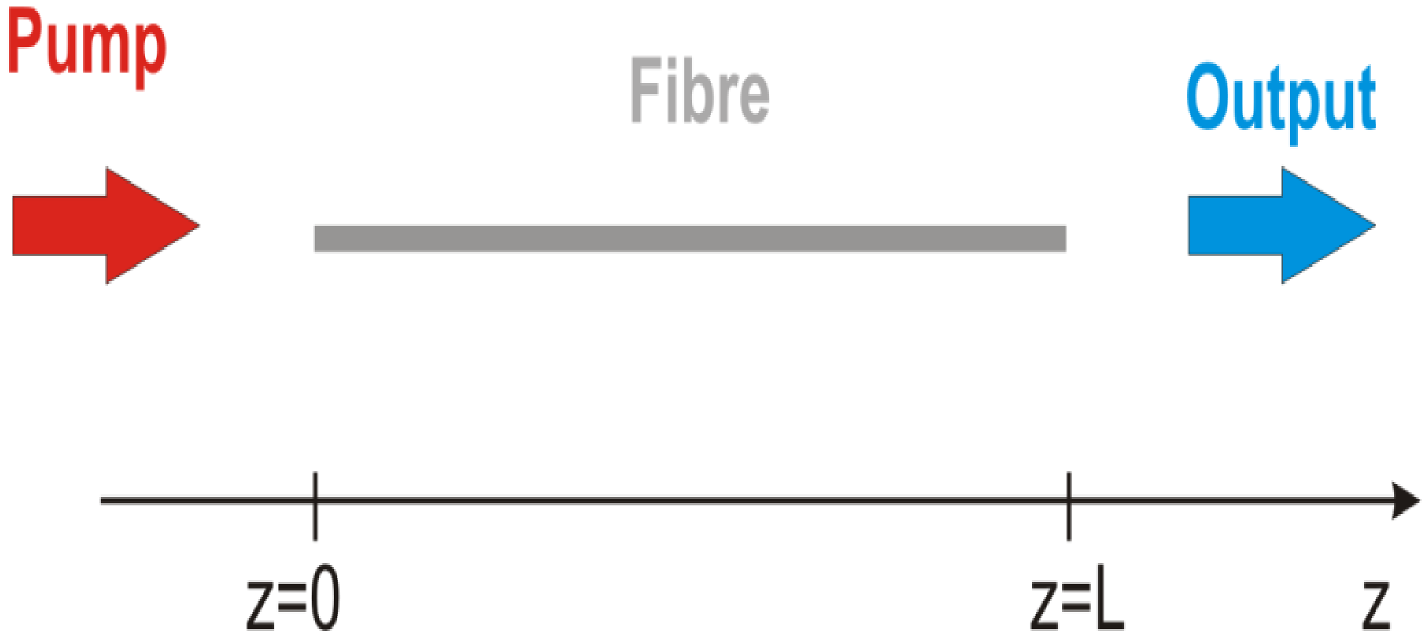
Dy^{3+} doped chalcogenide glass fibre pumped at one end (z=0). We wish to calculate the output power collected at z = L.



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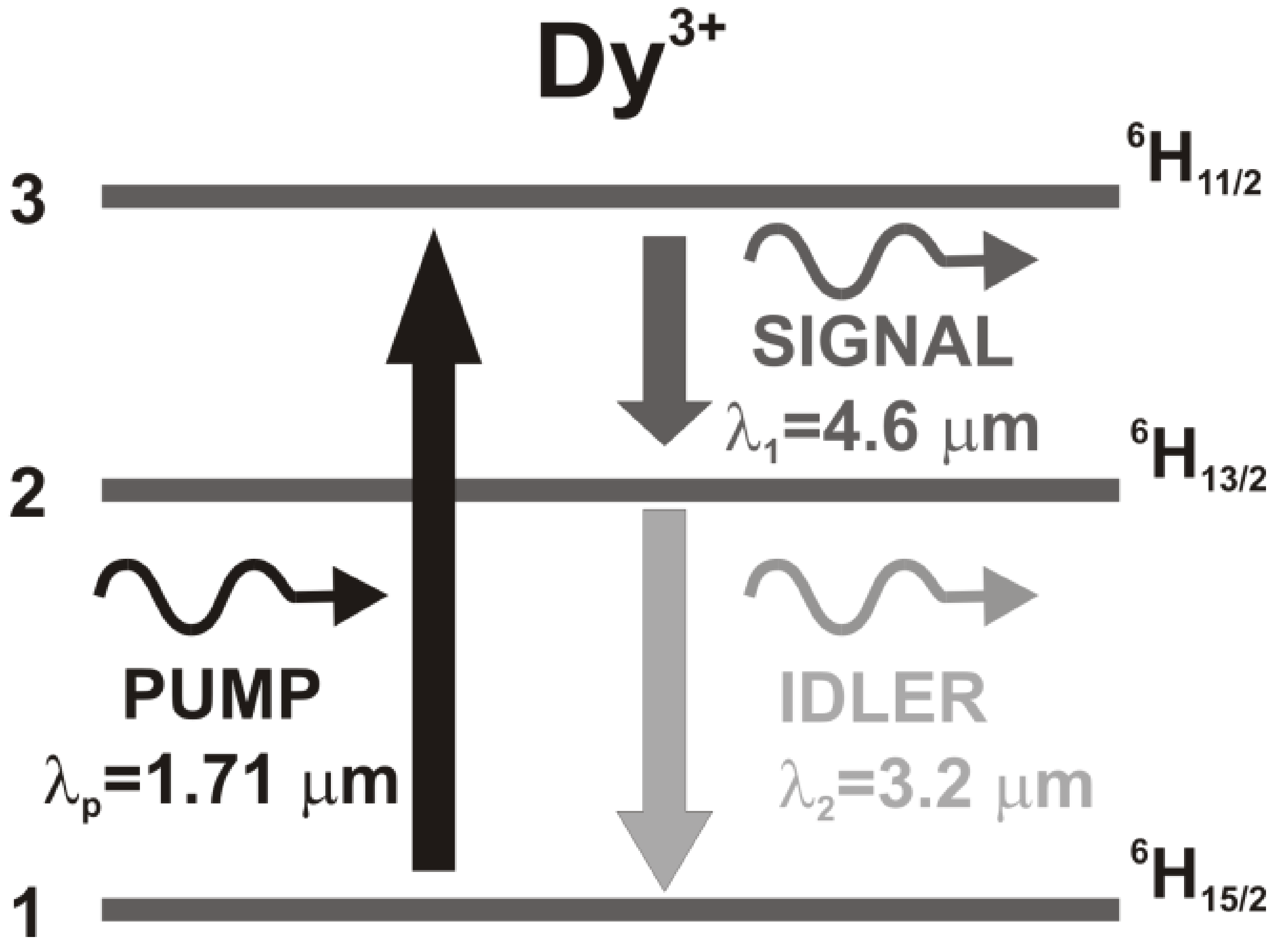
Test problem

Dysprosium ion energy levels model



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Test problem

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Dy^{3+}-ion concentration	$7x10^{19}$	cm^{-3}
Core radius	5.5	µm
Numerical aperture	0.2	
Cladding radius	30	µm
Fibre length L	2.1	m
Fibre loss at all wavelengths	1	dB/m
Lifetime of level 3	2	ms
Lifetime of level 2	5.2	ms
Branching ratio for 3-2 transitions	0.15	
reflectivity for idler, signal and pump at z = 0	0.2	
reflectivity for idler, signal and pump at z = L	0.2	

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Test problem

Confinement factor for signal (λ_1)	0.8	
Confinement factor for idler (λ_2)	0.9	
Confinement factor for pump	0.034	
Pump wavelength	1.71	μm
Signal wavelength (λ_1)	4.6	μm
Idler wavelength (λ_2)	3.35	μm
Pump emission cross section	0.318×10^{-20}	cm^2
Pump absorption cross section	0.501×10^{-20}	cm^2
Idler emission cross section	0.912×10^{-20}	cm^2
Idler absorption cross section	0.485×10^{-20}	cm^2
Signal emission cross section	0.097×10^{-20}	cm^2
Signal absorption cross section	0.016×10^{-20}	cm^2

Test problem

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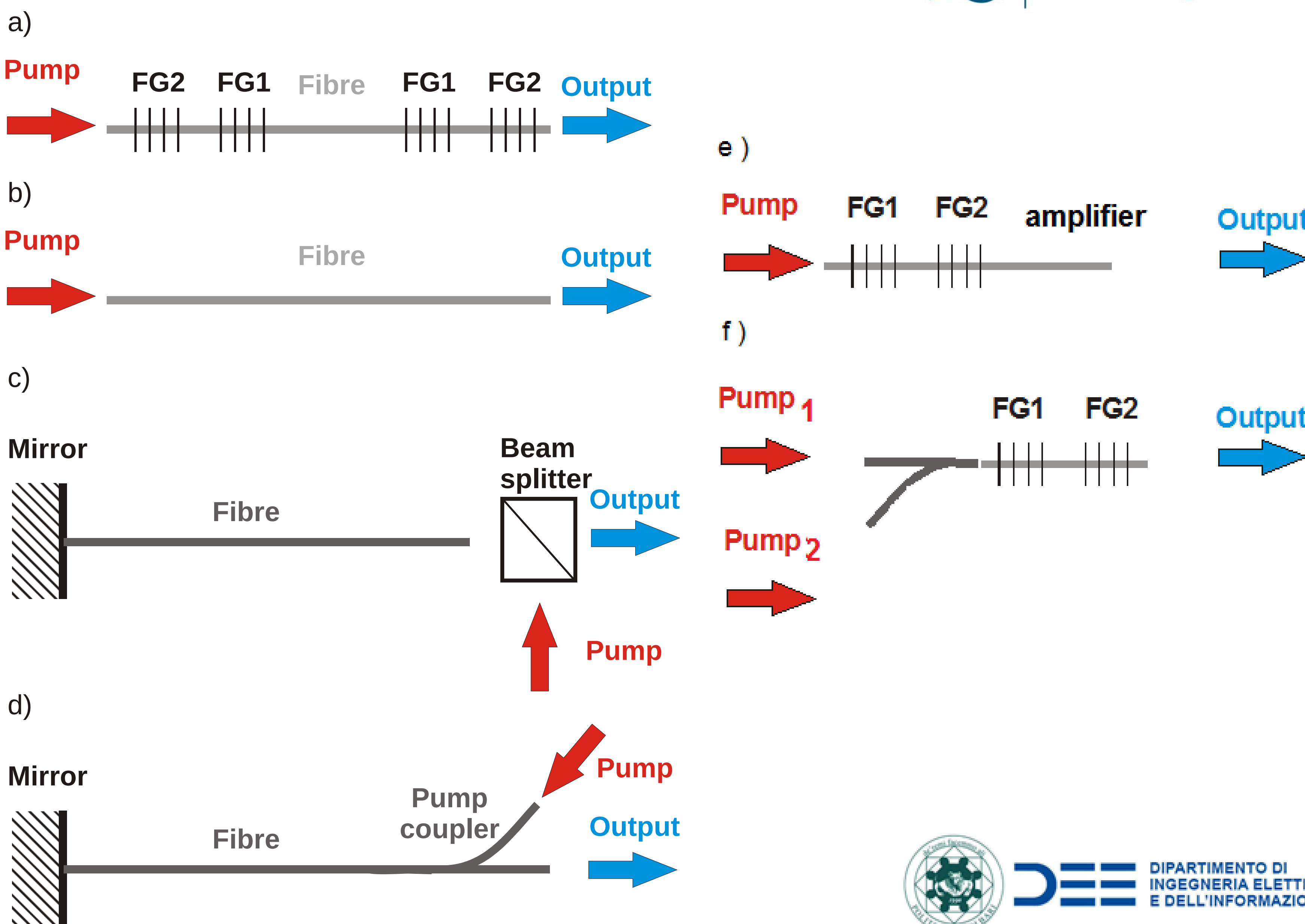

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Method of Single Expression

(NPU,NIT,KUT)

Conditions of single-frequency radiation from fiber laser: Modelling by the Method of Single Expression

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Modelling methods of optical characteristics

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Beam propagation is the most efficient.
For fibers, the well known split-step Fourier method is often quite suitable.
A lot of phenomena can be investigated with numerical beam propagation.
Simulation software will often only offer single-pass propagation,
but not the calculation of self-consistent steady-state solutions for lasers.

Dr. Rüdiger Paschotta

https://www.rp-photonics.com/tutorial_modeling3.html

For self-consistent steady-state numerical modelling we are planning to use the method of single expression (MSE), what is taking into account contra directions waves' propagation without division on forward and backward propagating waves.

Fiber Optics Communication Laboratory

Concise description of the method of single expression (MSE)

$$\frac{d^2\dot{E}_x(z)}{dz^2} + k_0^2\tilde{\varepsilon}_i(z)\,\dot{E}_x(z) = 0$$ **Helmholtz's equation**

where $\tilde{\varepsilon}_i = \varepsilon_i' + j\varepsilon_i''$

Traditionally the general solution of Helmholtz's equation is presented as the sum of two contra-propagating plane waves:

$$\dot{E}_x(z) = E_0^+ \cdot e^{-jk_i z} + E_0^- \cdot e^{jk_i z}$$

where $k_i = k_0\sqrt{\tilde{\varepsilon}_i}$

In the **MSE** the component of electric field is presented in the following form:

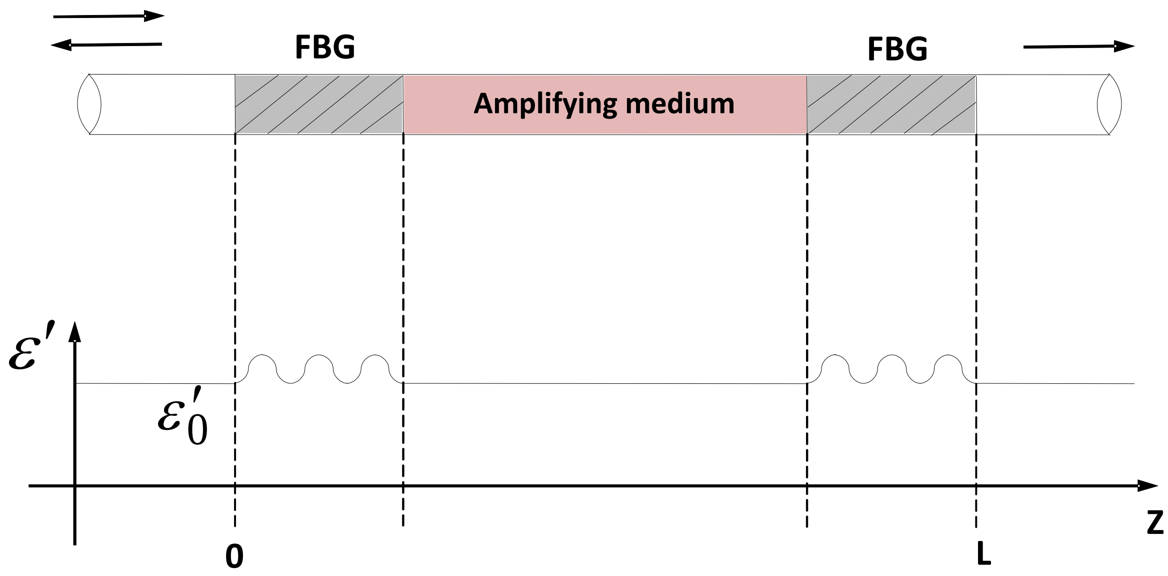
$$\dot{E}_x(z) = U(z)\cdot\exp\left(-jS(z)\right)$$

This single expression describes resultant field amplitude and phase in a medium without division on oppositely – propagating waves. By inserting this expression in Helmholtz's equation the following set of differential equations is obtained:

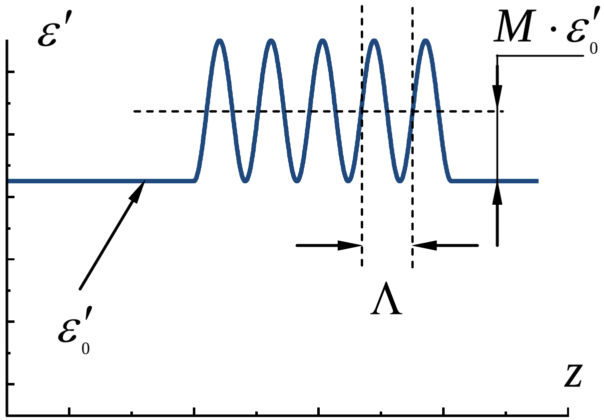
H.V. Baghdasaryan, Method of backward calculation, in the book: *Photonic Devices for Telecommunications: how to model and measure*/ Editor G.Guekos, Springer-Verlag, 1999.

H.V. Baghdasaryan, T.M. Knyazyan. Problem of plane EM wave self-action in multilayer structure: An exact solution, *Optical and Quantum Electronics*, 1999.

Fiber laser structure under analysis



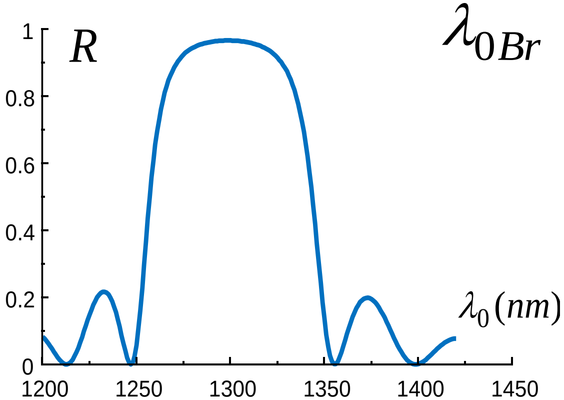
Single sinusoidal fiber Bragg grating (FBG)

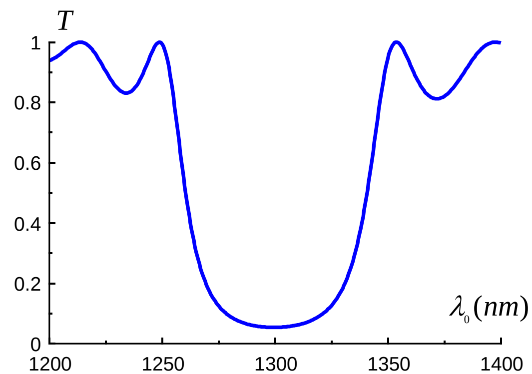


$$\varepsilon' = \varepsilon'_0 \cdot (1 + M + M \cdot \sin(2\pi \frac{z}{\Lambda} - \frac{\pi}{2}))$$

$$\Lambda = \frac{\lambda_{0Br}}{2\sqrt{\varepsilon'_0 + M \cdot \varepsilon'_0}}$$

$$\lambda_{0Br} = 1300$$





Number of periods $N = 30$

$\Lambda = 413.167$ nm

$M = 0.1$ $\quad \varepsilon'_0 = 2.25$ $\quad \varepsilon'' = 0$

$L_{FBG} = 30 \times \Lambda = 12395.01$ nm

Electric field distribution in single sinusoidal fiber Bragg grating (FBG)

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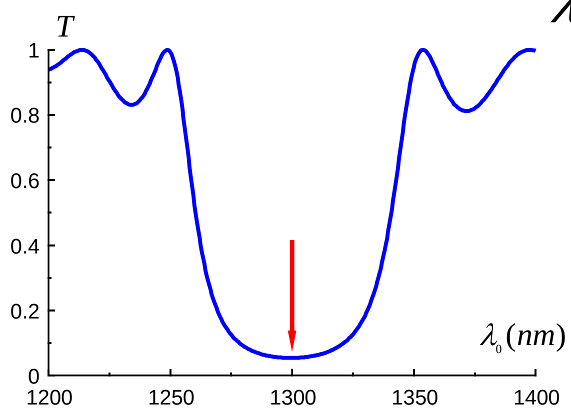
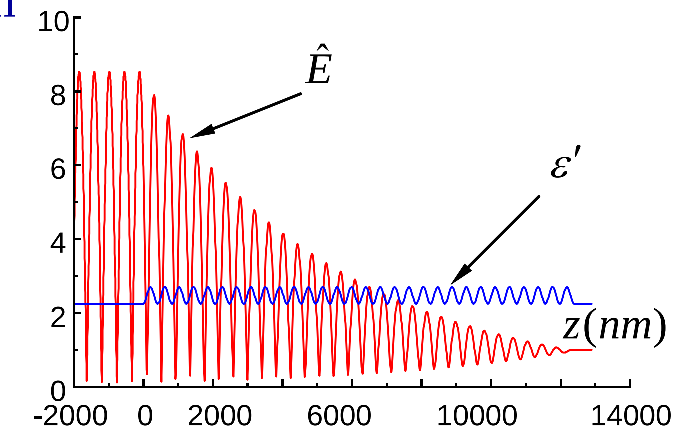
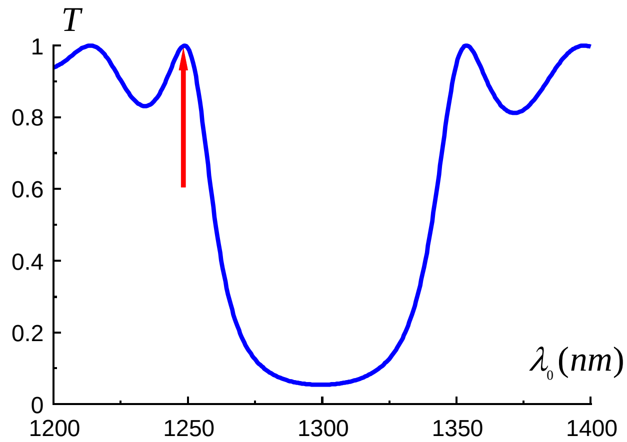
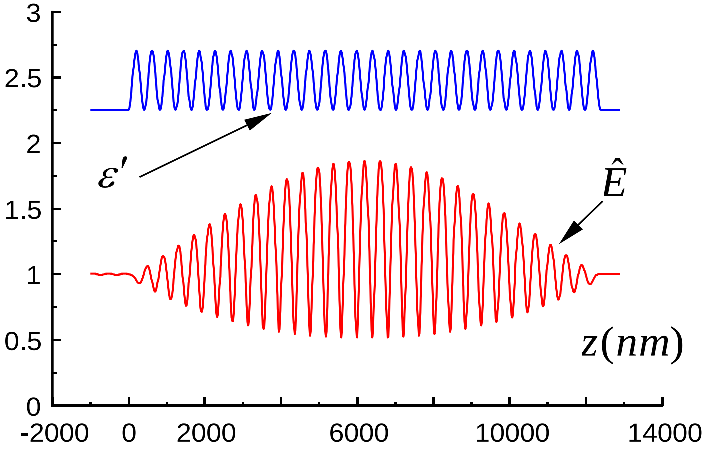
$\lambda_{0Br} = 1300$ nm









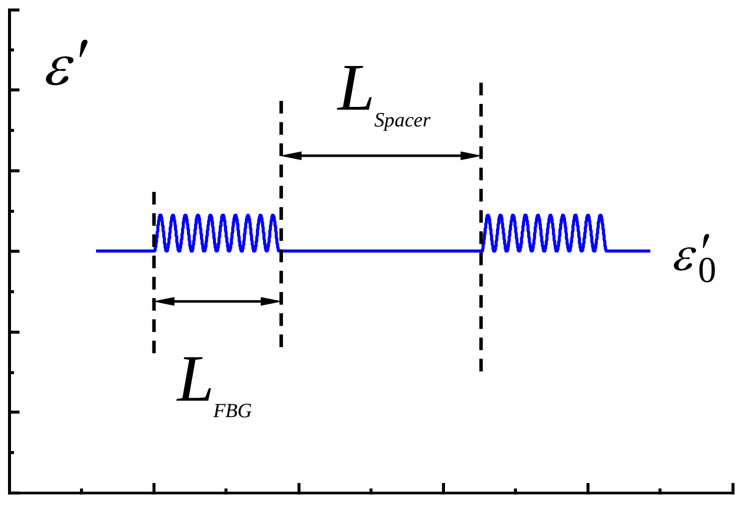
Number of periods $N = 30$

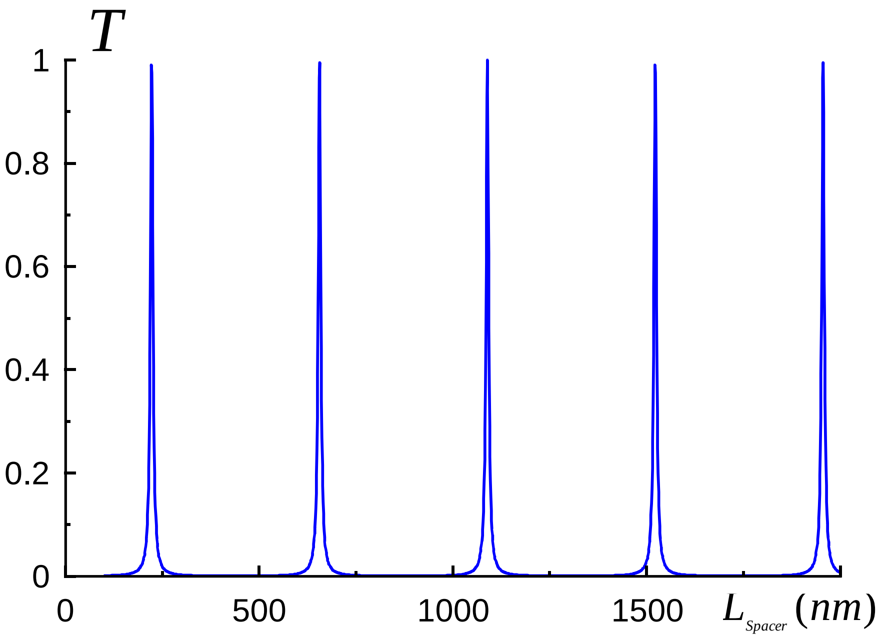
$\Lambda = 433.33$ nm

$M = 0.1$ $\quad \varepsilon_0' = 2.25$ $\quad \varepsilon'' = 0$

$L_{FBG} = 30 \times \Lambda = 12395.01$ nm

Fiber laser structure under analysis





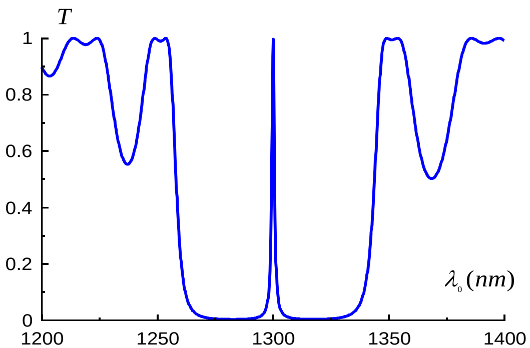
Transmittance of FBG-Spacer-FBG from the length of spacer

Maximal transmissions are observed at:

$$L_{Spacer} = m \cdot \frac{\lambda_0}{2\sqrt{\varepsilon_{Spacer}}} + \frac{\lambda_0}{4\sqrt{\varepsilon_{Spacer}}}, \quad \mathrm{m} = 0,1,2,3....$$

Single frequency radiations are observed at these resonant lengths of spacer.

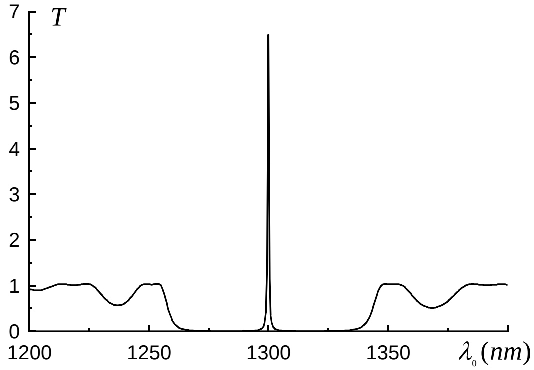
Transmittance of FBG-spacer -FBG structure without and with amplification in spacer



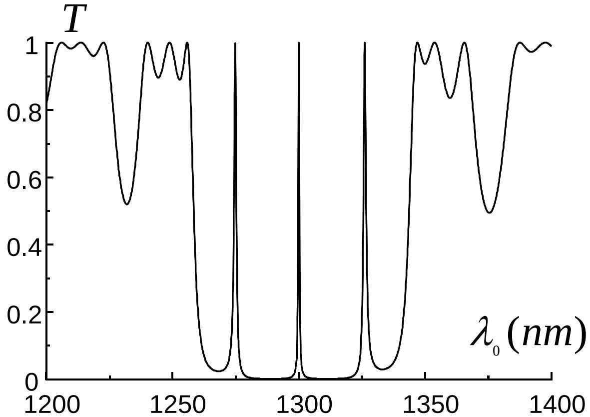
$\varepsilon'' = 0$

$$L_{Spacer} = 1955.5 \text{ nm}$$

$$L_{spacer} < L_{FBG}$$



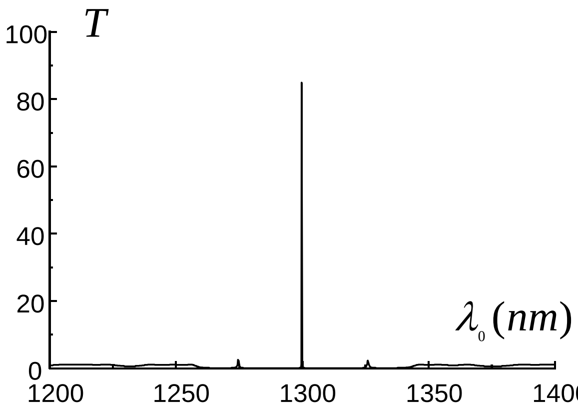
$\varepsilon'' = 0.005$



$\varepsilon'' = 0$

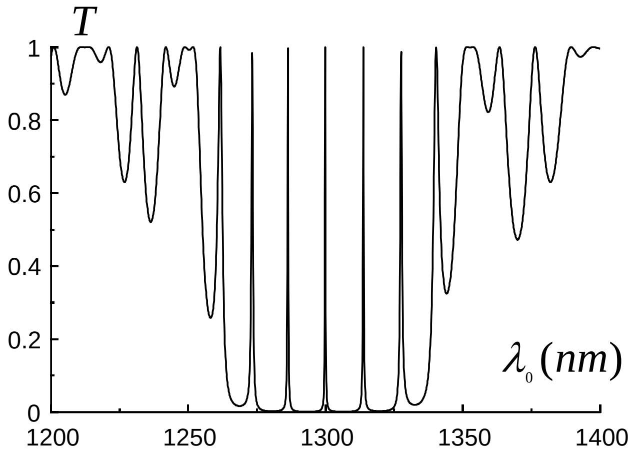
$$L_{Spacer} = 15389 \text{ nm}$$

$$L_{FBG} < L_{spacer} < 2L_{FBG}$$



$\varepsilon'' = 0.001$

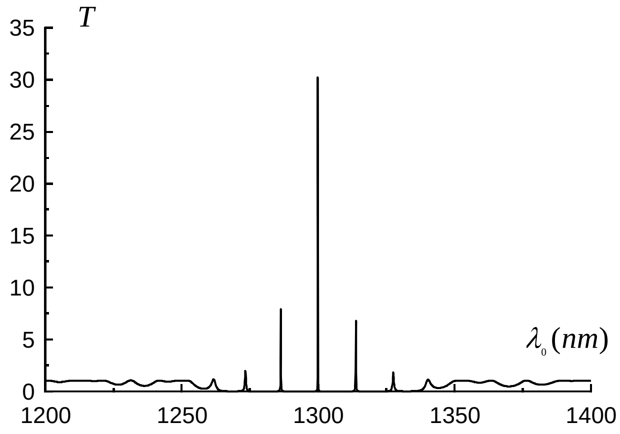
Transmittance of FBG-spacer -FBG structure without and with amplification in spacer



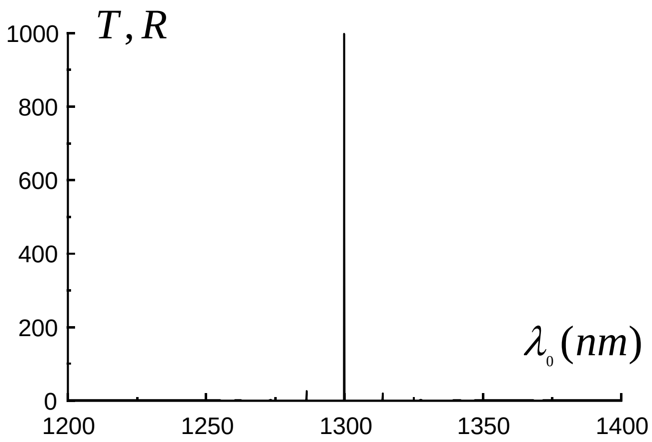
$\varepsilon'' = 0$

$L_{Spacer} = 34886$ nm

$2L_{FBG} < L_{spacer} < 3L_{FBG}$



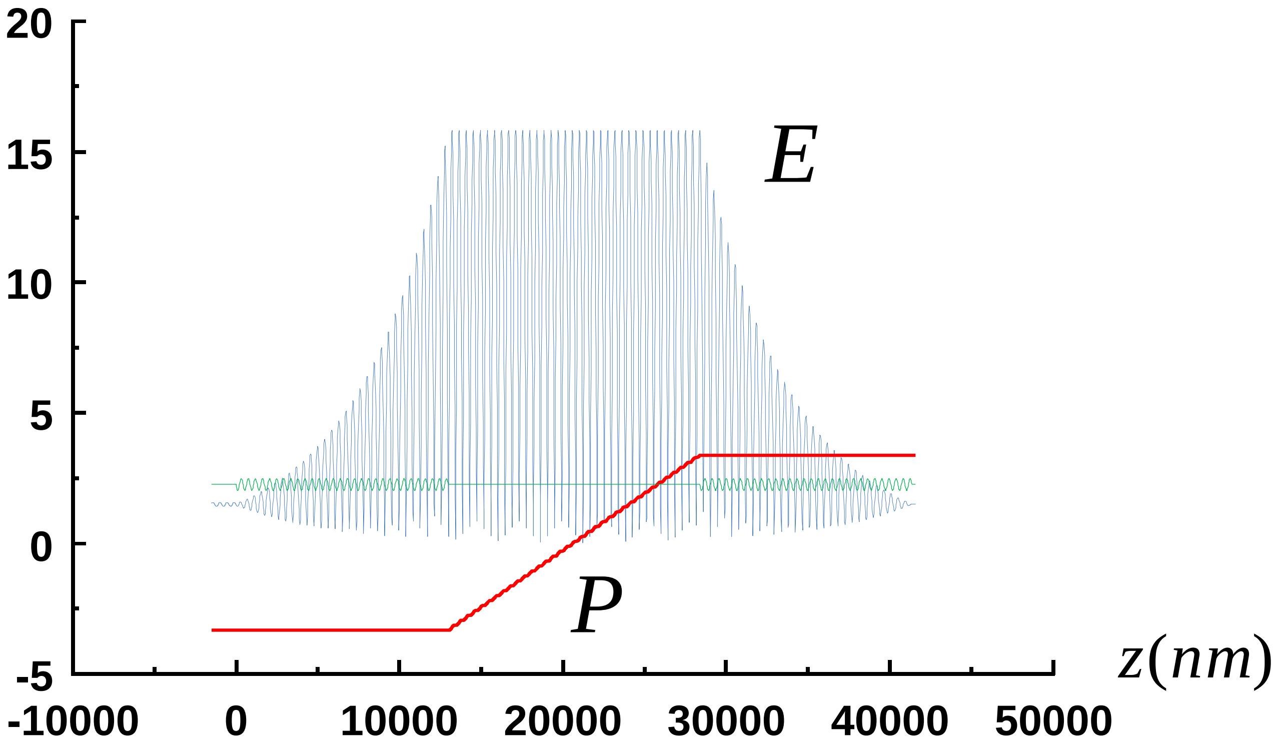
$\varepsilon'' = 0.0004$



$\varepsilon'' = 0.0005$

Single frequency radiation along fiber.

Distributions of electric field **E** and Poynting vector **P** along FBG-amplifying fiber-FBG structure



$$\varepsilon'' = 0.0005$$

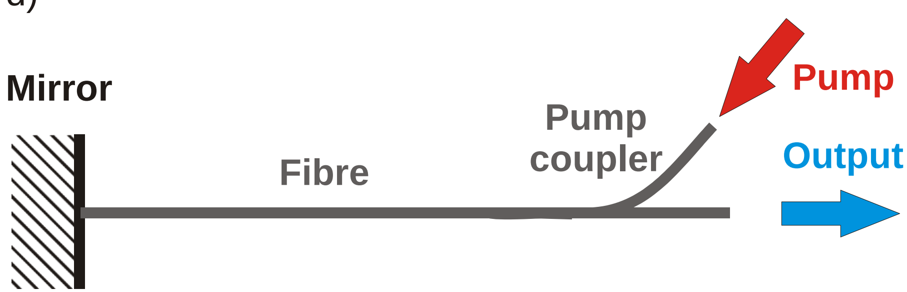
Test problem

a)

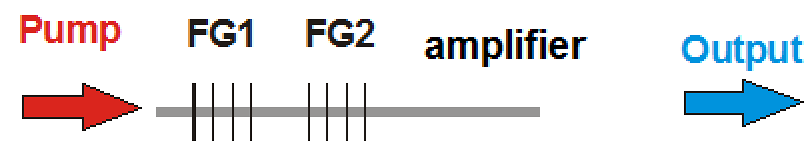
b)

c)

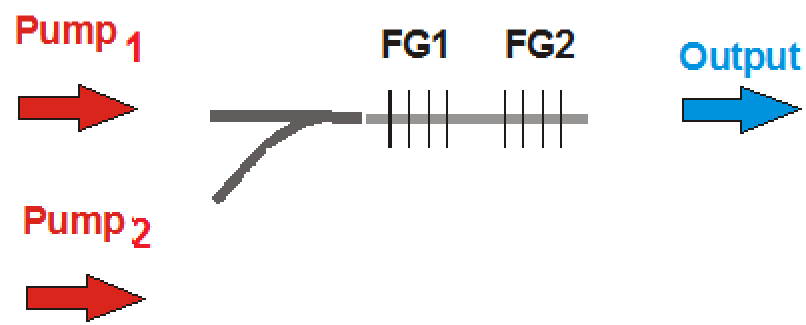
d)



e)



f)



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Test problem

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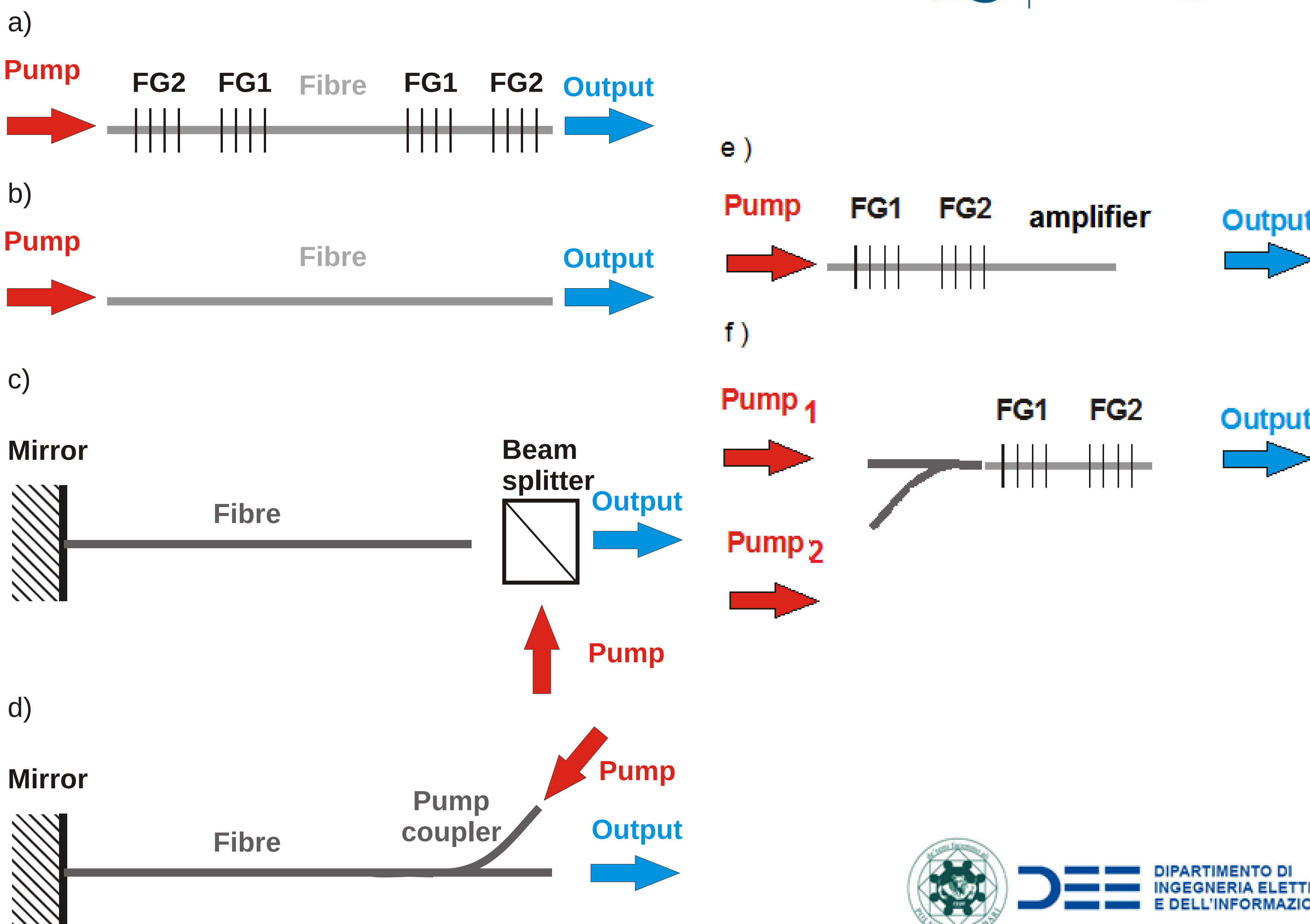

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Relaxation Method (PB)

Test problem

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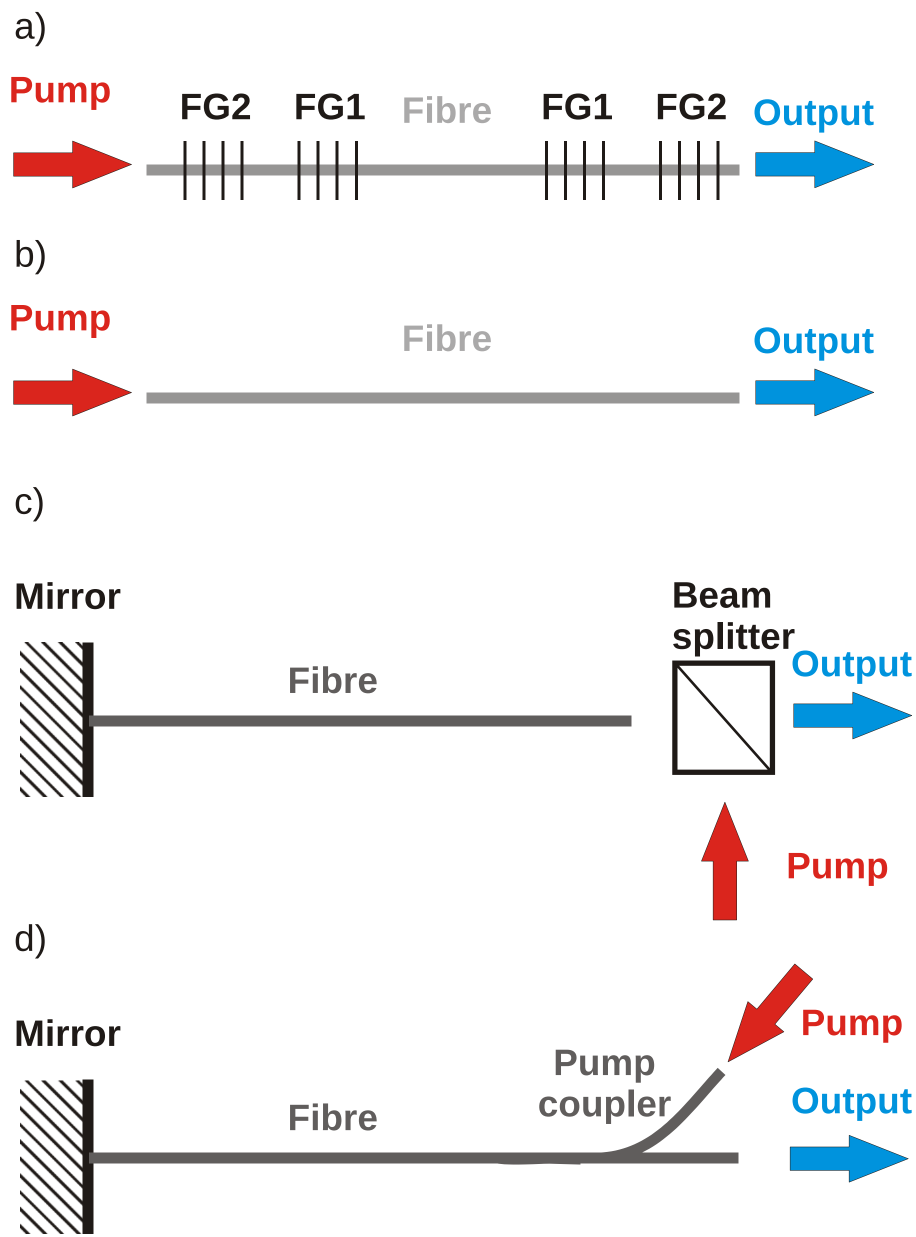

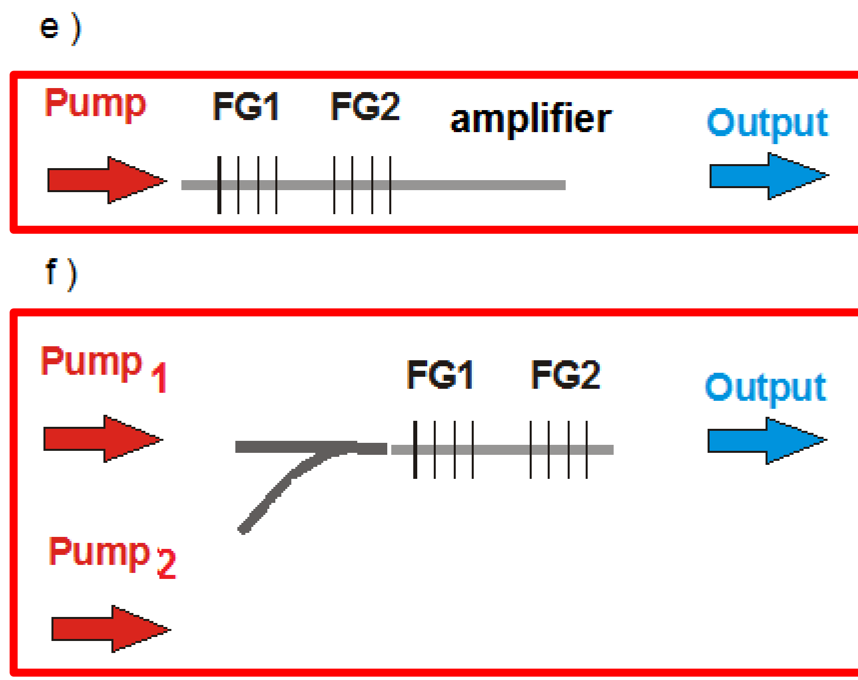

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Test problem for configuration (e)

Parameter	Value	Measure unit
Dy^{3+}-ion concentration	6×10^{25}	ions/m^3
Fiber laser cavity length	0.12	m
Fiber amplifier length	1	m
Fiber losses at all wavelengths	1	dB/m
Lifetime of level 3	1.5	ms
Lifetime of level 2	7.0	ms
Branching ratio for 3→2 transition	0.088	
Reflectivity for signal at $z = 0$	0.99	
Reflectivity for signal at $z = L$	0.70	

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Test problem for configuration (e)

Parameter	Value	Measure unit
Pump wavelength λ_p	1709	nm
Signal wavelength λ_s	4384	nm
Confinement factor for pump	0.694	
Confinement factor for signal	0.662	
Pump absorption cross section	5.96×10^{-25}	m^2
Pump emission cross section	2.62×10^{-25}	m^2
Signal absorption cross section	7.32×10^{-25}	m^2
Signal emission cross section	1.09×10^{-24}	m^2

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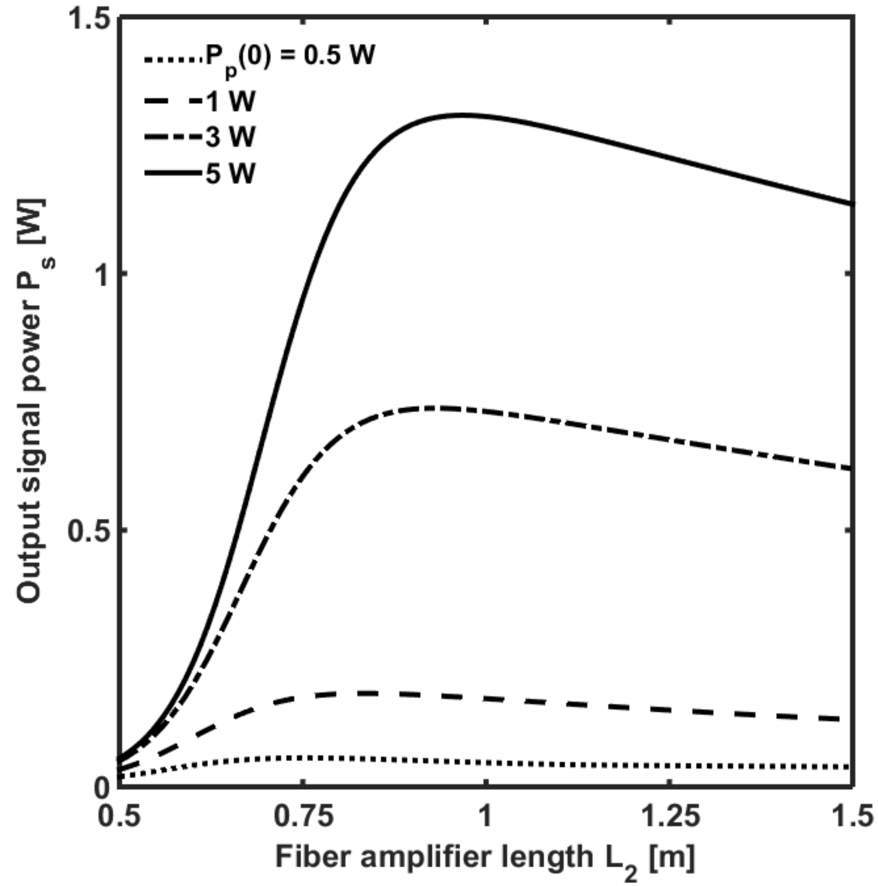
Test problem for configuration (e)



Output signal power P_s versus amplifier length L_2, for different input pump powers $P_p(0)$ = 0.5 W (dotted curve), $P_p(0)$ = 1 W (dashed curve), $P_p(0)$ = 3 W (dash-dot curve), $P_p(0)$ = 5 W (solid curve).

Test problem for configuration (f)

Parameter	Value	Measure unit
Dy^{3+}-ion concentration	4×10^{25}	$ions/m^3$
Fiber laser cavity length	0.5	m
Fiber losses at all wavelengths	3	dB/m
Lifetime of level 3	1.5	ms
Lifetime of level 2	7.0	ms
Branching ratio for $3 \rightarrow 2$ transition	0.088	
Reflectivity for signal at $z = 0$	0.99	
Reflectivity for signal at $z = L$	0.30	

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Test problem for configuration (f)

Parameter	Value	Measure unit
Pump 1 wavelength λ_{p1}	2850	nm
Pump 2 wavelength λ_{p2}	4092	nm
Signal wavelength λ_s	4384	nm
Confinement factor for pump 1	0.68	
Confinement factor for pump 2	0.665	
Confinement factor for signal	0.662	
Pump 1 absorption cross section	1.33×10^{-24}	m^2
Pump 1 emission cross section	9.79×10^{-25}	m^2
Pump 2 absorption cross section	3.39×10^{-25}	m^2
Pump 2 emission cross section	2.10×10^{-25}	m^2
Signal absorption cross section	7.32×10^{-25}	m^2
Signal emission cross section	1.09×10^{-24}	m^2

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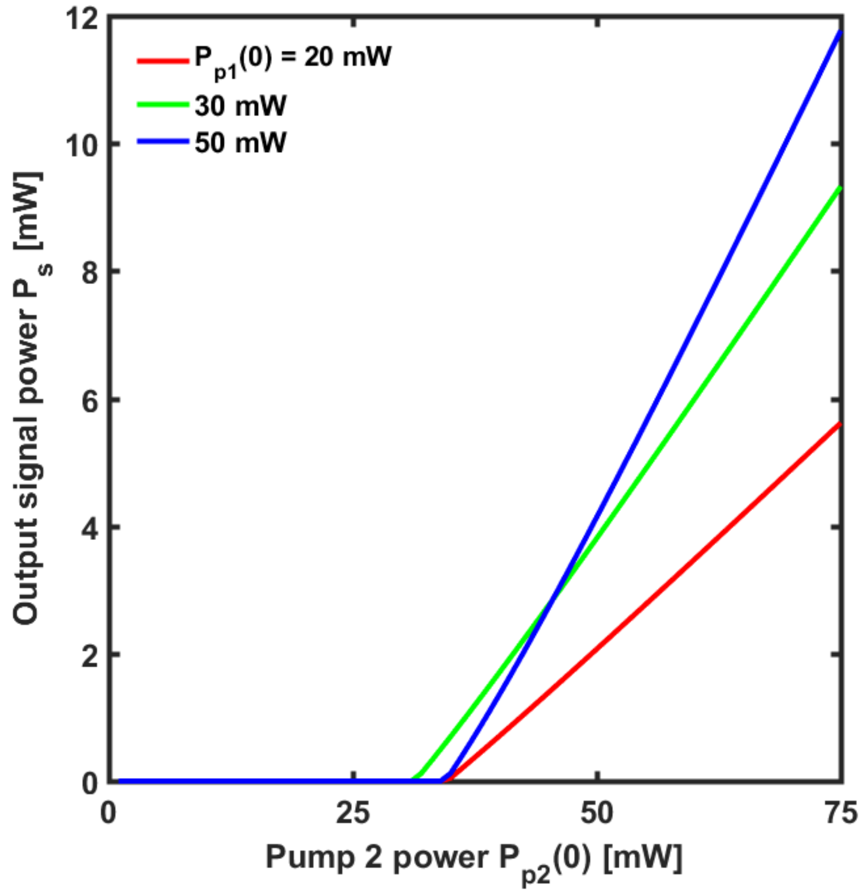
Test problem for configuration (f)



Optical signal power P_s versus the input pump #2 power $P_{p2}(0)$, for different input pump #1 powers, $P_{p1}(0)$ = 20 mW (red curve), $P_{p1}(0)$ = 30 mW (green curve), $P_{p1}(0)$ = 50 mW (blue curve).

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Relaxation Method (NU, WrUT)

Test problem

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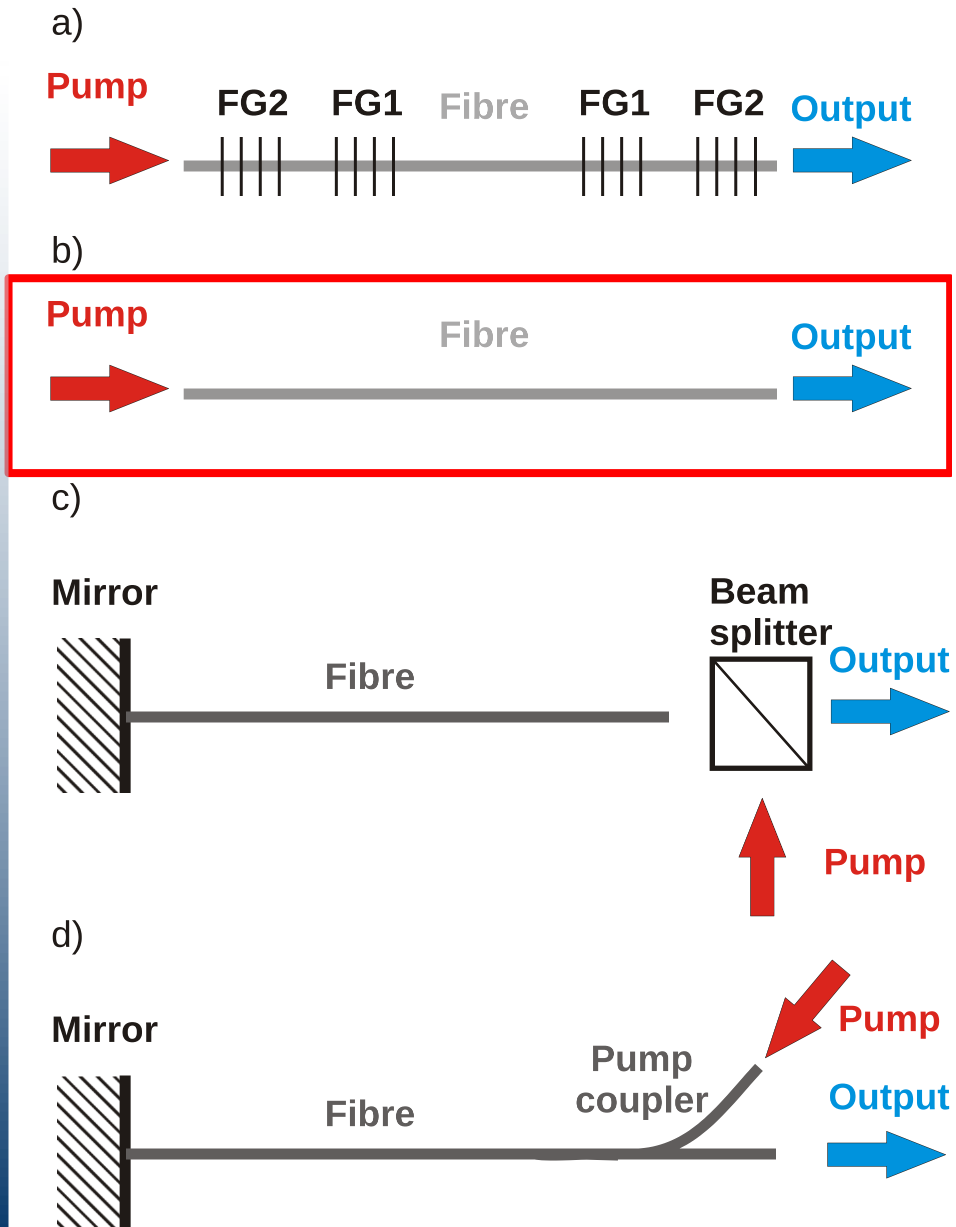

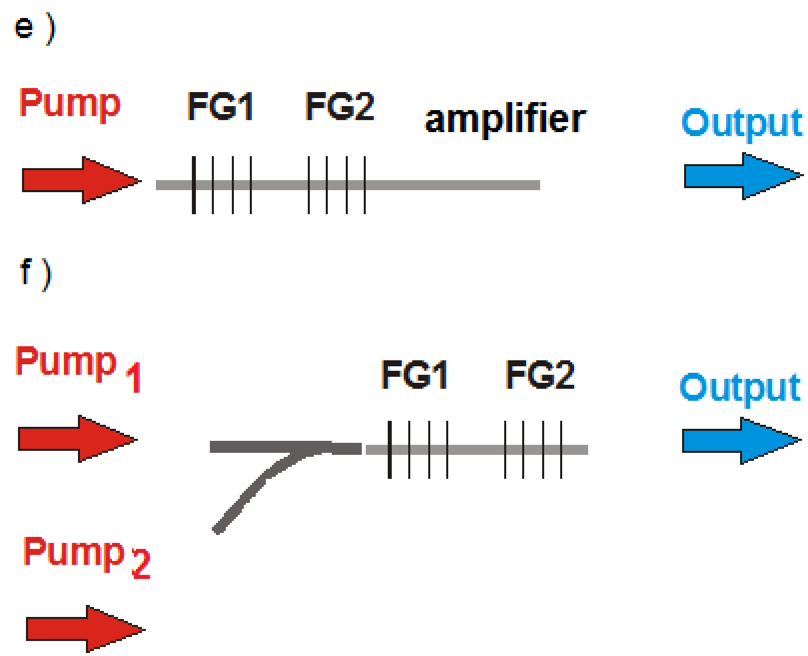

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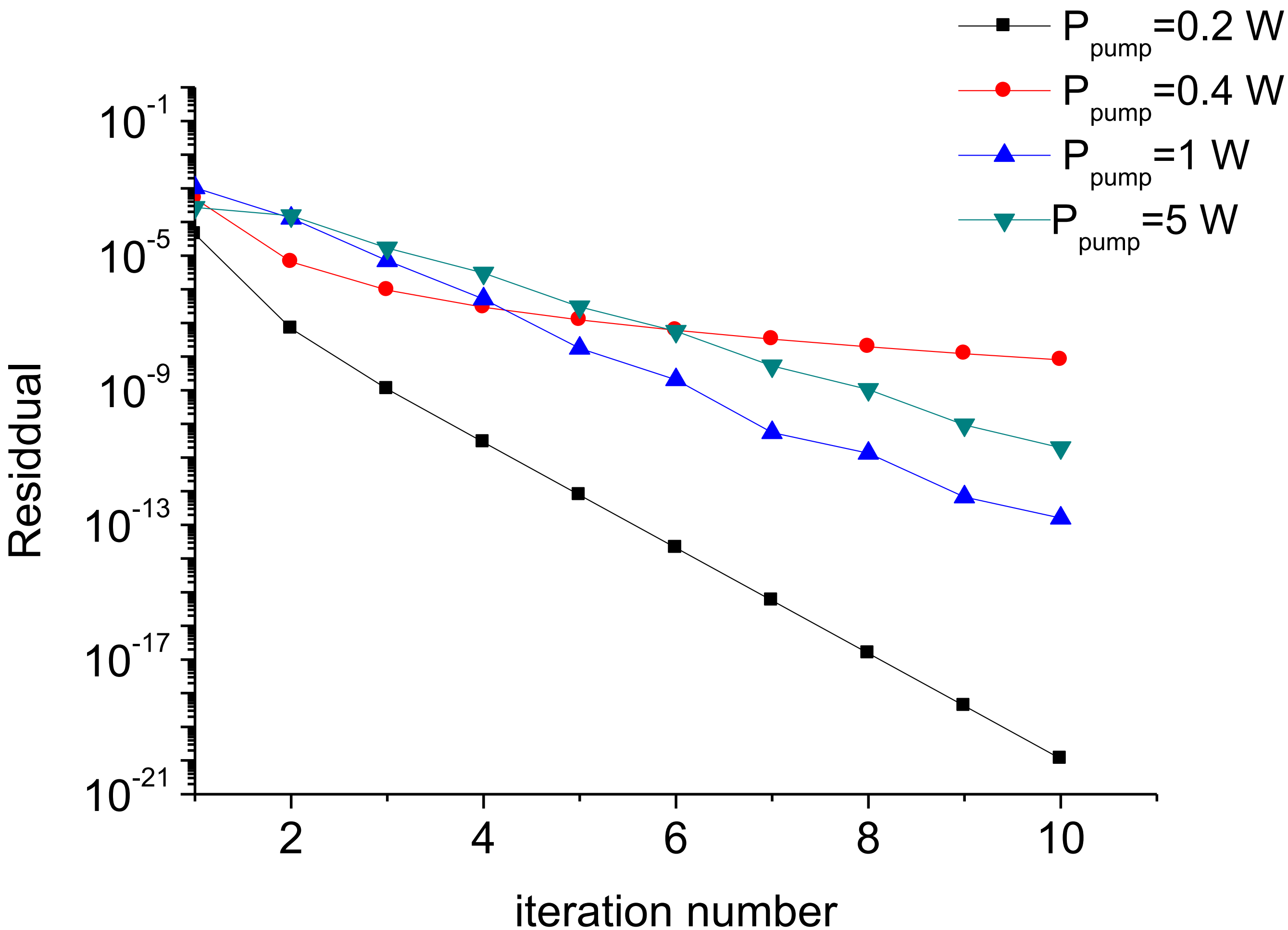
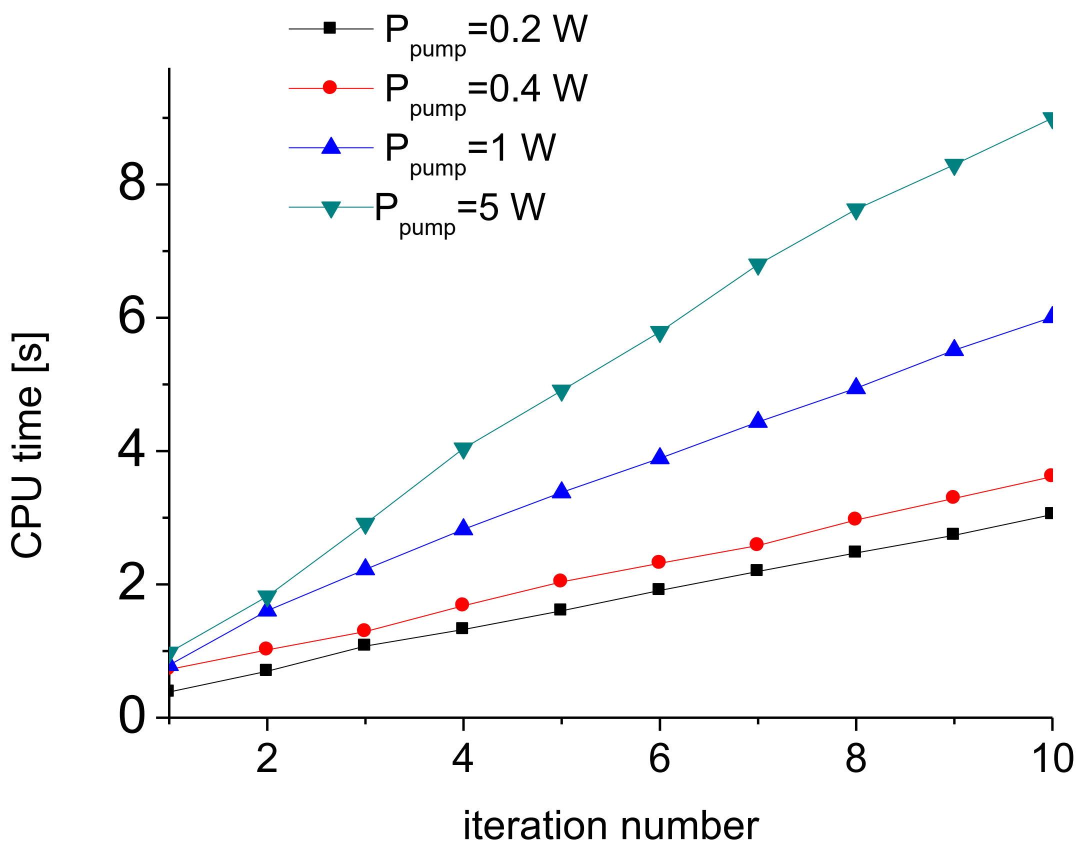
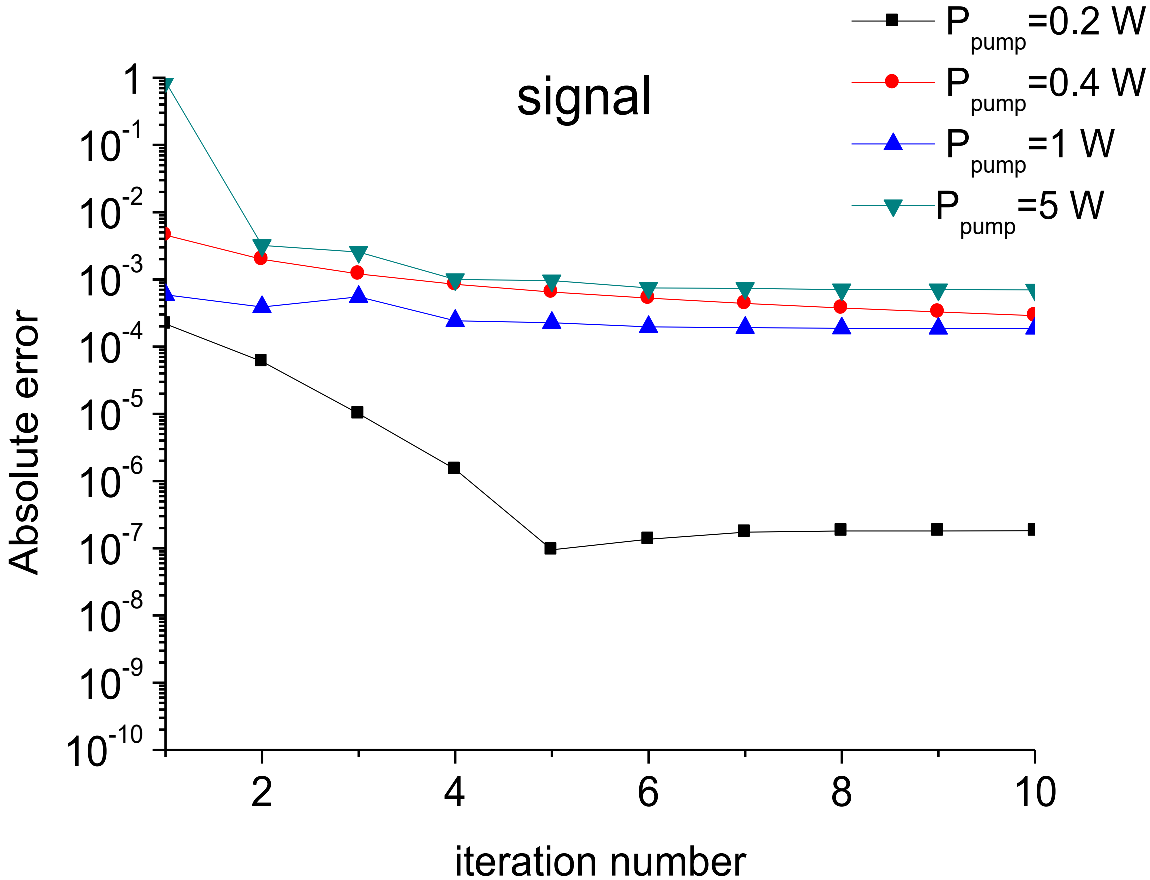
Numerically calculated dependence of the residual



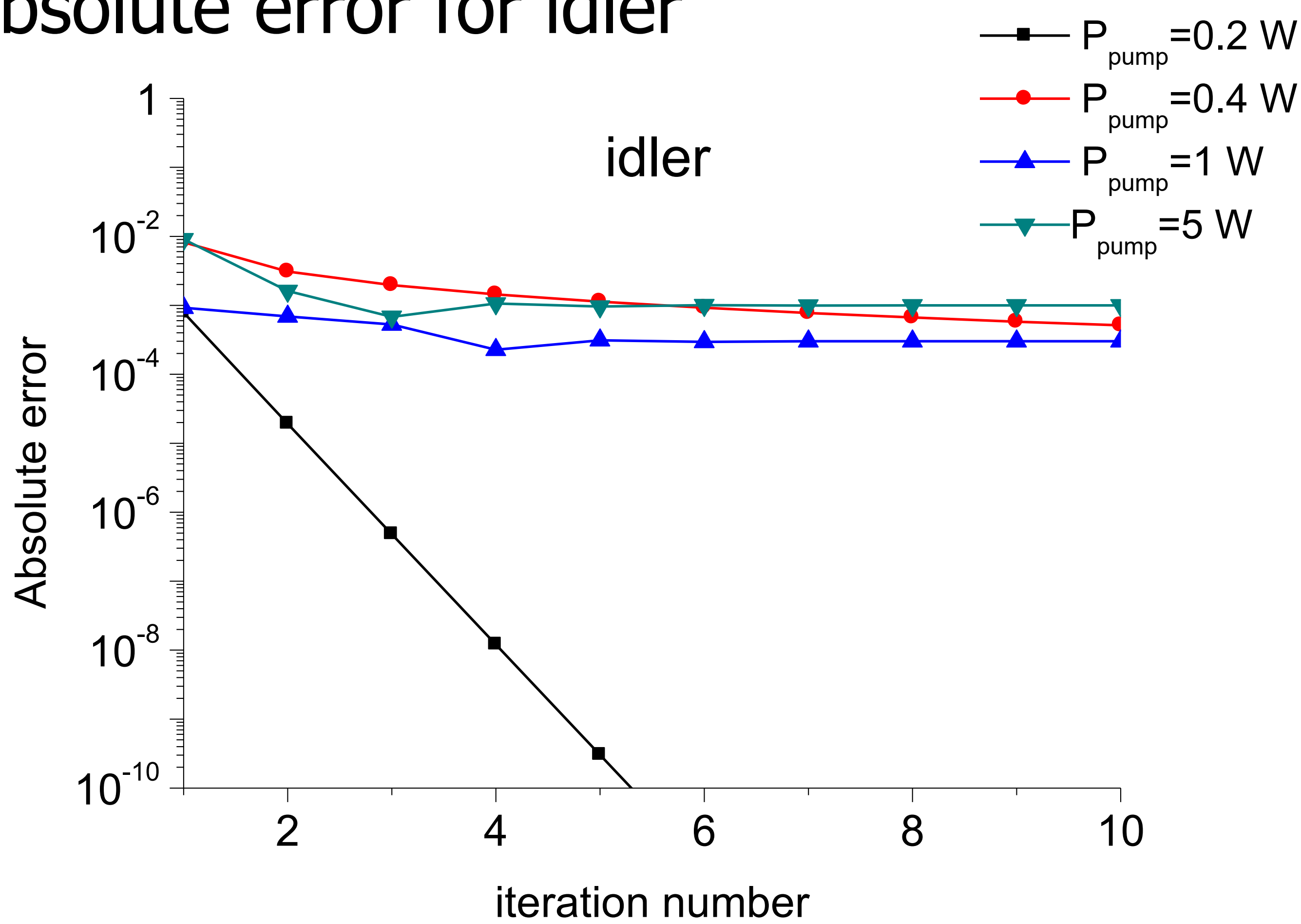
Numerically calculated dependence of the CPU time



Numerically calculated dependence of the absolute error for signal



Numerically calculated dependence of the absolute error for idler



Summary

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