Mode-instability induced Bragg gratings in fiber lasers: Numerical modelling of their reflectivity

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Content

Spontaneous laser line sweeping (SLLS) What is it ?

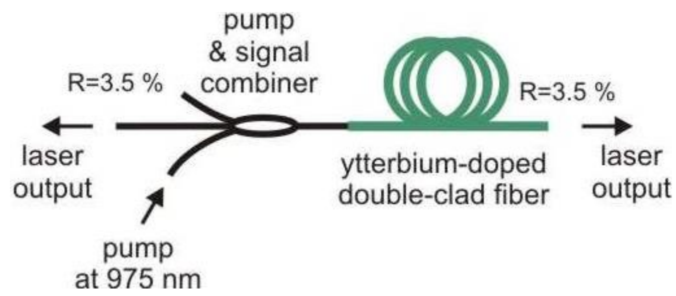
Self-pulsing regime:
self-sustained relaxation oscillations coexist with spectacular laser line drift

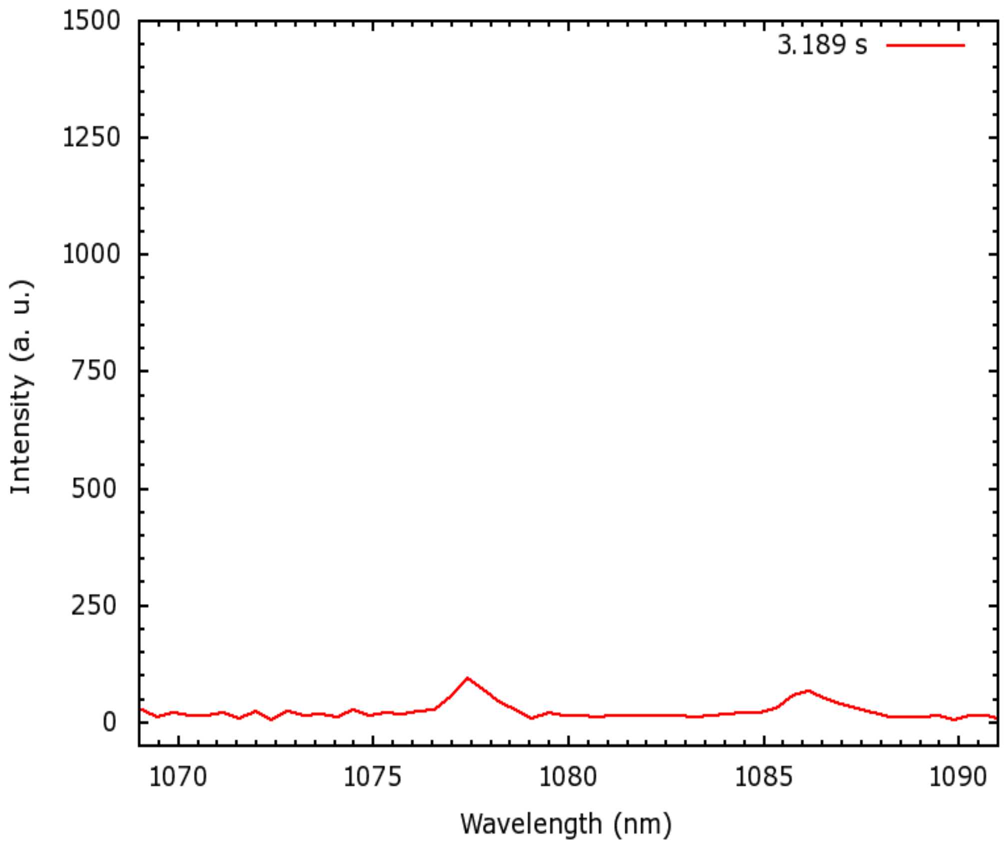
periodic drift of laser wavelength across up to ~20 nm nanometers and fast backward jump

narrow linewidth (<10 MHz), typically single frequency operation

Example:
SLLS in Yb fiber laser

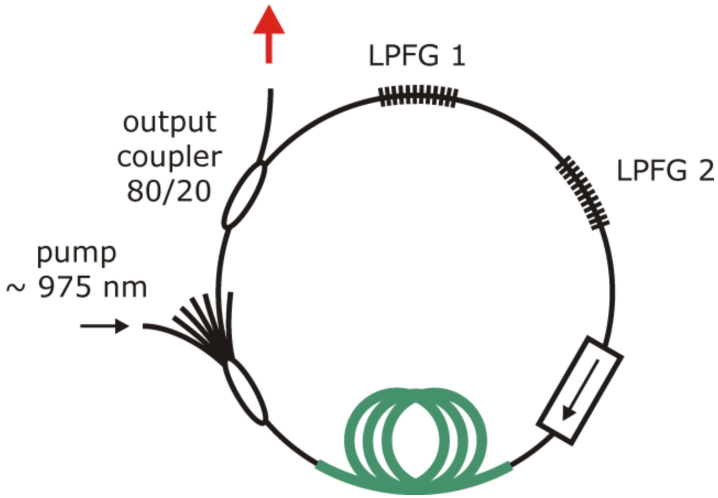
CCD spectrometer
resolution ~1 nm





Examples of self-swept lasers

1970's Ruby laser sweep range ~20 pm only
Antsiferov et al., Sov. JQE 1973



SLLS in fiber lasers:

Ytterbium

ring YDFL, broad sweep range **1076-1084** nm

P. Peterka et al., Laser Phys. Lett. 2009, first explanation in Las. Phys. Lett. 2012

Fabry-Perot YDFL with ytterbium GT-Wave fiber bundle

Kir'yanov and Il'ichev, Laser Phys. Lett 2011

Fabry-Perot YDFL excellent SLLS explanation

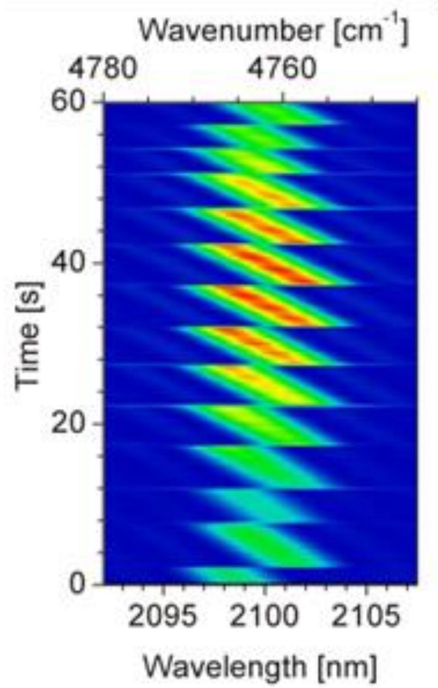
Lobach et al, Opt-Express 2011

Erbium near 1560 nm
Peterka et al., Proc. SPIE, 2012

Thulium 1915 – 1930 nm
Wang et al., Opt. Express 2013

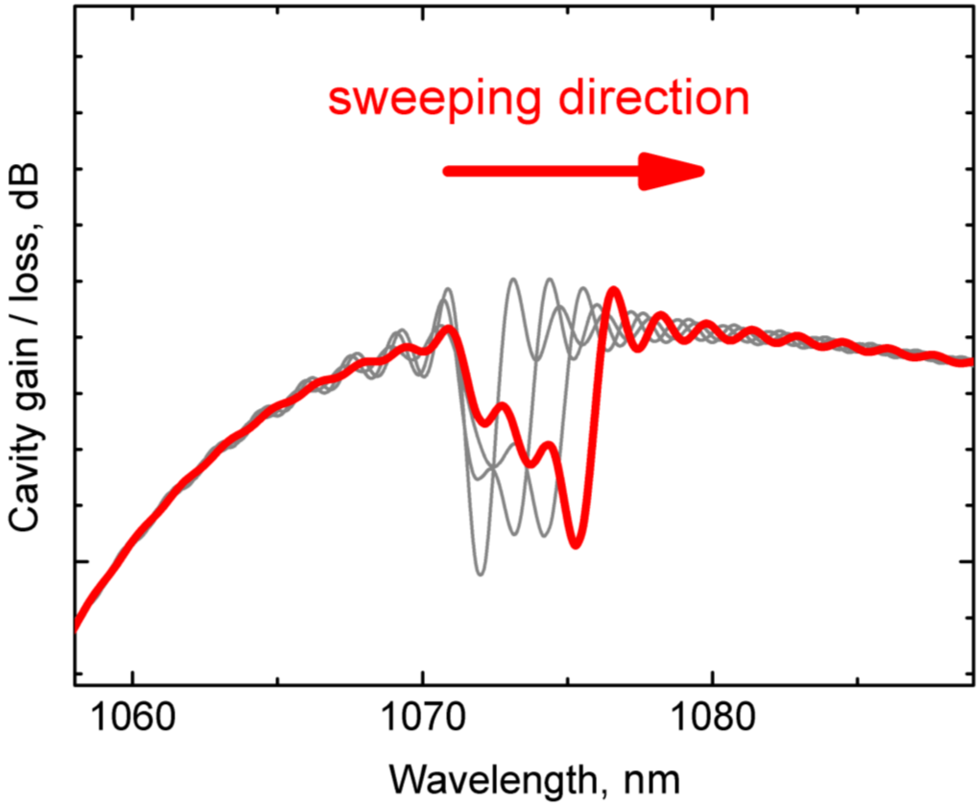
Bismuth near 1460 nm
Lobach et al., Opt. Express 2015

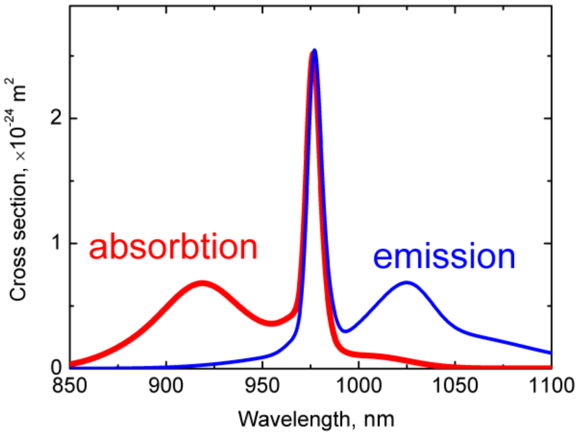
Holmium near 2100 nm
Aubrecht et al., Opt. Express 2017

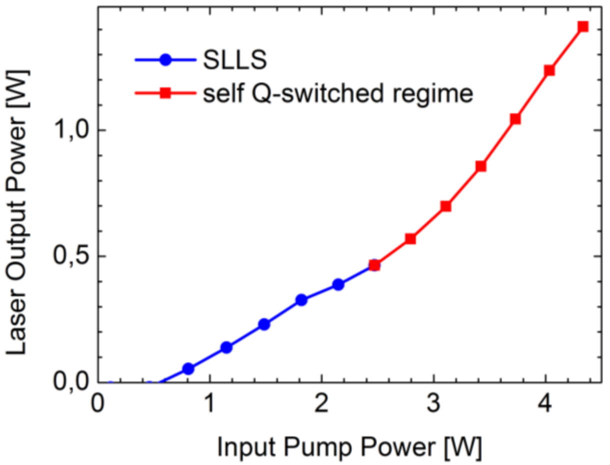


Spatial hole burning (SHB) in the active fiber

Ytterbium fiber as an example
spectral features not in scale MHz vs. nm







Qualitative SHB model:

Antsiferov et al., Soviet J. Quantum Electron. 1973.
A. Lobach et al., Opt. Express 2011
Navratil et al. Laser Phys. Lett., 2017

Motivation

- Contribution to laser physics fundamentals. First evidence of FBG in the active medium of the laser.

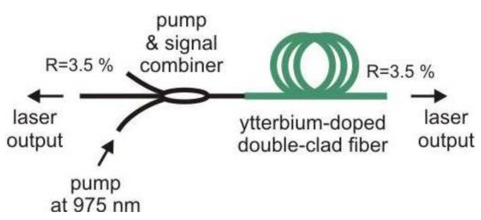
- Understanding fiber laser instabilities (self-Q-switching) and how to avoid them. SLLS is an undesired effect in YDFL intended for cw mode of operation Compare transverse vs. longitudinal mode-instability

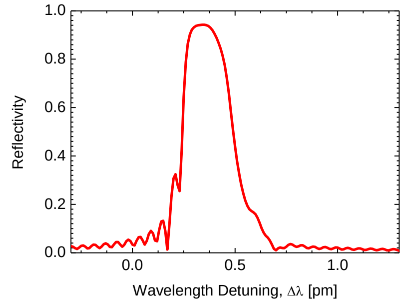
- Possible development of stable and cost-effective self-Q-switched fiber lasers

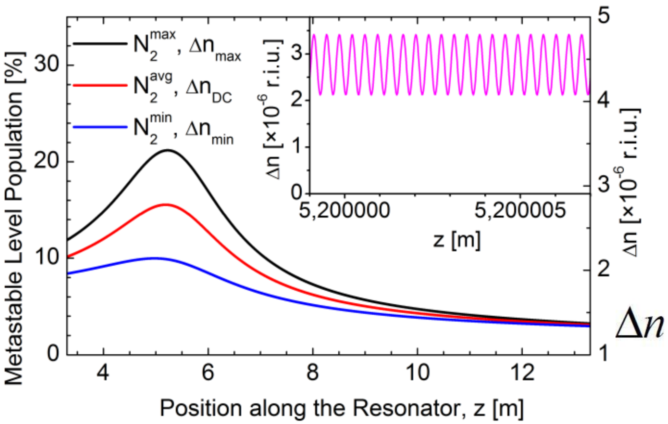
- Useful applications of swept lasers: interrogation of optical fiber sensor systems, laser spectroscopy (narrow linewidth), coherent spectral analyzers, Brillouin OSA

Mode-instabilities (MI)

Longitudinal MI



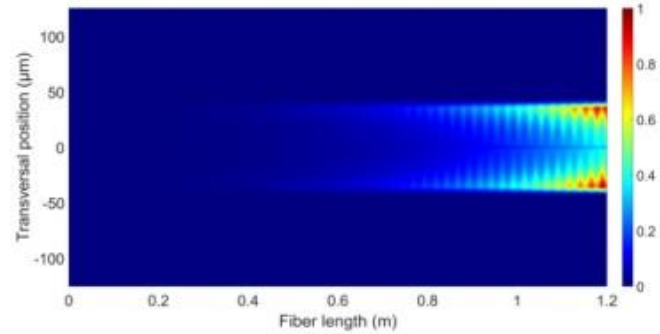




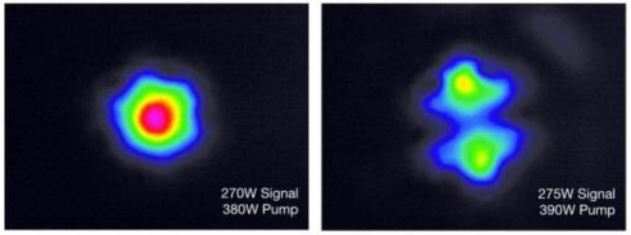
$$\Delta n = \frac{e^2 (n_0^2 + 2)^2}{72 n_0 m \varepsilon_0 c_0} S N_2$$

fiber grating pitch close λ/2
The grating couples different longitudinal modes of the fiber core propagating in the opposite direction (it works in reflection).
Peterka et al, Optics Express 2014 and 2016, Proc. SPIE 2015

Transverse MI



C. Jauregui et al,," Opt. Express 24, 7879 (2016).

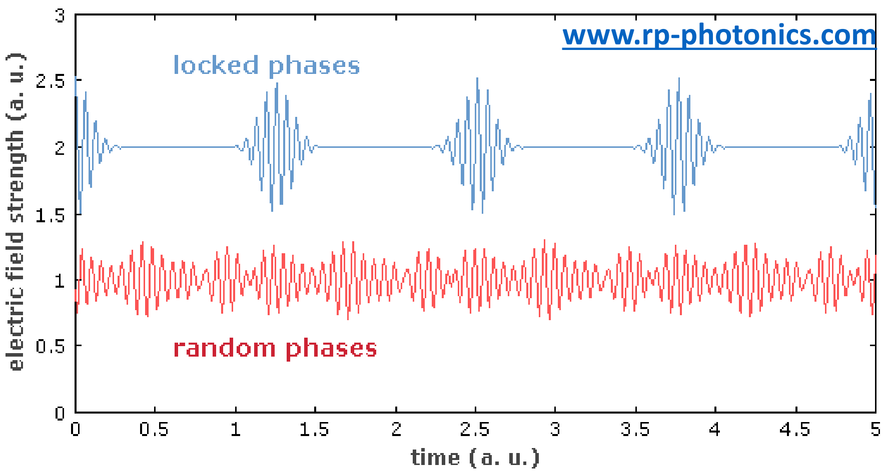


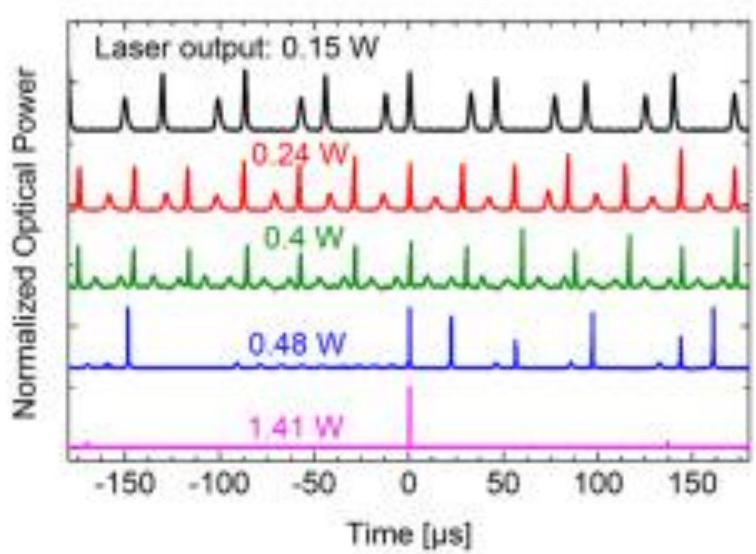
T. Eidam et al, Optics Express 19, 13218 (2011).

fiber grating pitch » λ
Such grating has automatically the right period to couple different core modes propagating in the same direction (it works in transmission).
A. V. Smith & J.J. Smith, Optics Express 19, 10180 (2011).
T. Eidam et al, Optics Express 19, 13218 (2011).

Special cases of longitudinal mode-instabilities

mode-locking ← regime → (self)mode-sweeping
mode-locked lasers ← devices → self-swept lasers





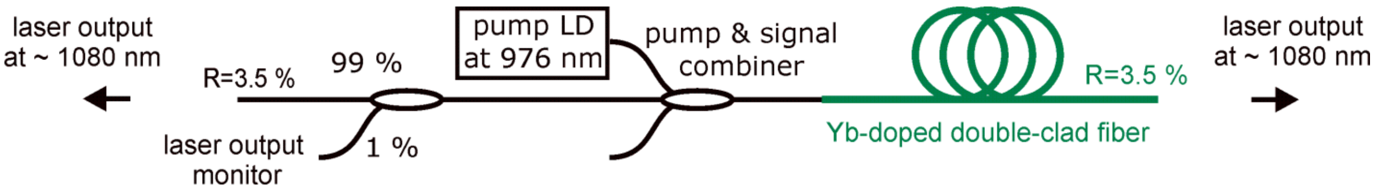
longitudinal modes oscillate all together and they are locked in phase. The spectrum is broad and the pulses are ultra-short.

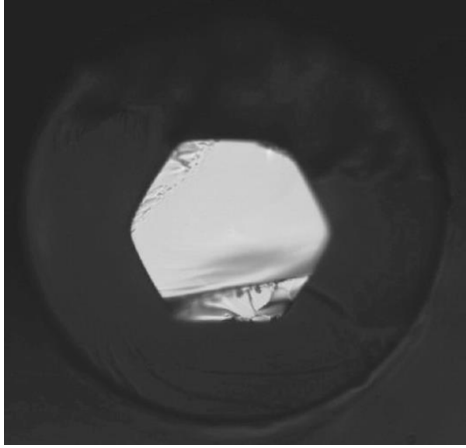
first experiments: Hargrove et al., Appl. Phys. Lett. 1964
M. DiDomenico, J. Appl. Phys. 1964

longitudinal modes oscillate coherently one by one. The spectrum is ultra-narrow (mostly single-frequency) and the pulses are broad.

Peterka et al, Laser Phys Lett. 2009, 2012
Kir'yanov and Il'ichev, Laser Phys. Lett 2011
Lobach et al, Optics Express 2011

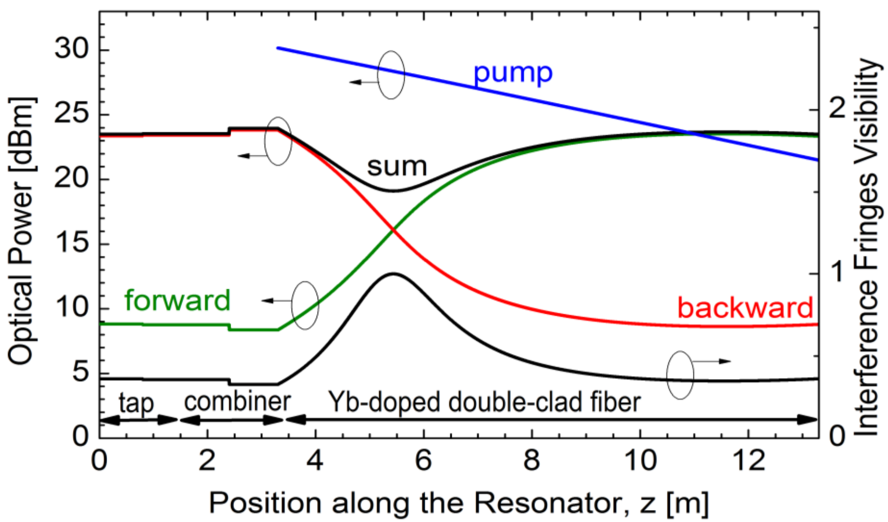
Theoretical model 1: fiber laser

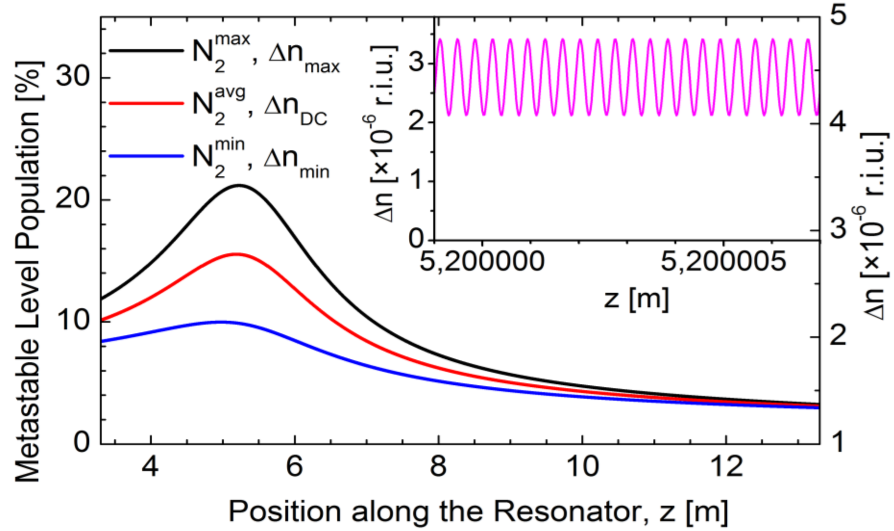




laser rate equations & propagation equations ⇒
inversion and optical power longitudinal evolution

$$\Delta n = \frac{e^2 (n_0^2 + 2)^2}{72 n_0 m \varepsilon_0 c_0} S\, N_2$$





Peterka et al, Adv. Photonics Congress 2014, Optics Express 2014 and 2016, Proc. SPIE 2015

Theoretical model 2: superimposed fiber Bragg gratings

Coupled Mode Theory
FBG with uniform grating pitch Λ_0

Othonos & Kalli, Fiber Bragg Gratings 1999
Marcuse, Theory of dielectric optical waveguides, 1991

$$\frac{da}{dz} = ia\sigma + ib\kappa\, e^{-i2z(\beta-\pi/\Lambda_0)}$$

$$\frac{db}{dz} = -ib\sigma - ia\kappa^*\, e^{i2z(\beta-\pi/\Lambda_0)}$$

a(z), *b(z)*: slowly varying amplitudes of the forward and backward (reflected) waves
σ, κ: "DC" and "AC" coupling coefficients

Modification for series of superimposed gratings with grating pitch Λ_m:

$$\Lambda_m = \frac{\lambda_m}{2n_m^{eff}} \approx \frac{\lambda_0 + m\Delta\lambda}{2n_0^{eff}}$$

$$\Delta n_{AC}(z) = \sum_{m=1}^{N_{mod}} D(z) e^{-\frac{(m-1)T}{\tau_{FBG}}} \sin\left(\frac{2\pi}{\Lambda_m} z\right)$$

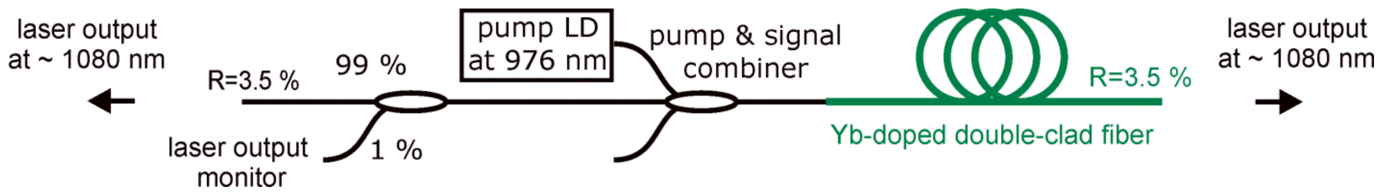
$$\frac{da}{dz} = ia\sigma + ib\kappa\, e^{-i2z\beta} \sum_{m=1}^{N_{\mathrm{mod}}} D e^{-\frac{(m-1)T}{\tau_{FBG}}} e^{iK_{m-1}z} =$$

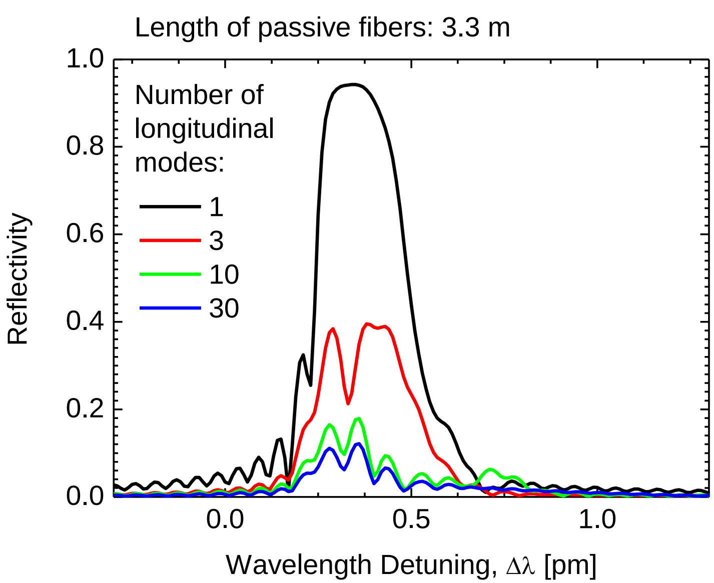
$$= a\sigma + ib\kappa D\, e^{-i2z\beta + iK_0 z}\left(1 + \sum_{m=1}^{N_{\mathrm{mod}}-1} e^{-\frac{mT}{\tau_{FBG}}} e^{i(K_m - K_0)z}\right)$$

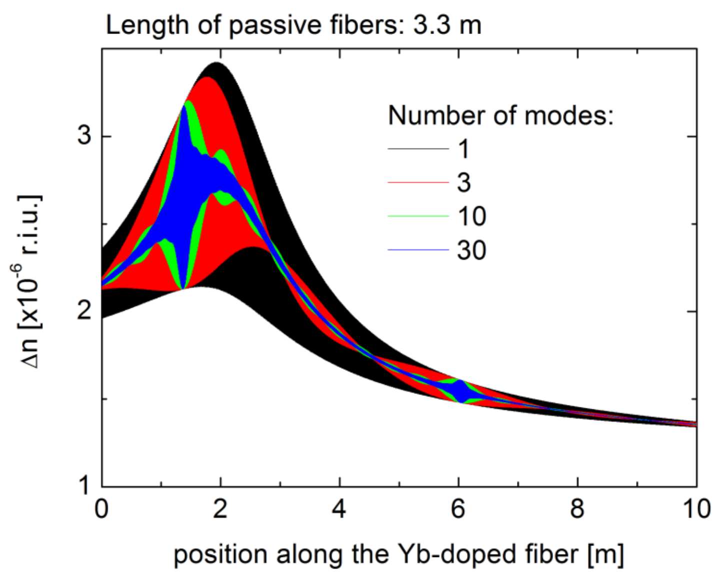
$$\frac{db}{dz} = -i\sigma b - ia\kappa^*\, e^{i2z\beta} \sum_{m=1}^{N_{\mathrm{mod}}} D e^{-\frac{(m-1)T}{\tau_{FBG}}} e^{-iK_{m-1}z}$$

$$K_m = \frac{2\pi}{\Lambda_m}$$

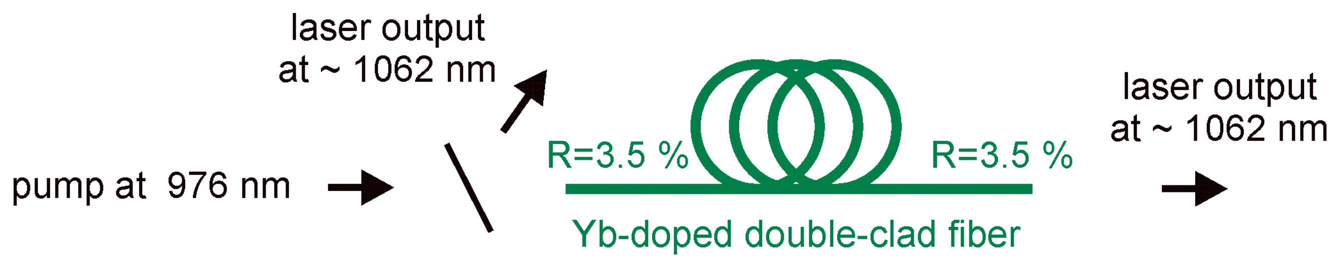
Reflectivity of FBGs in fiber laser with passive fibers

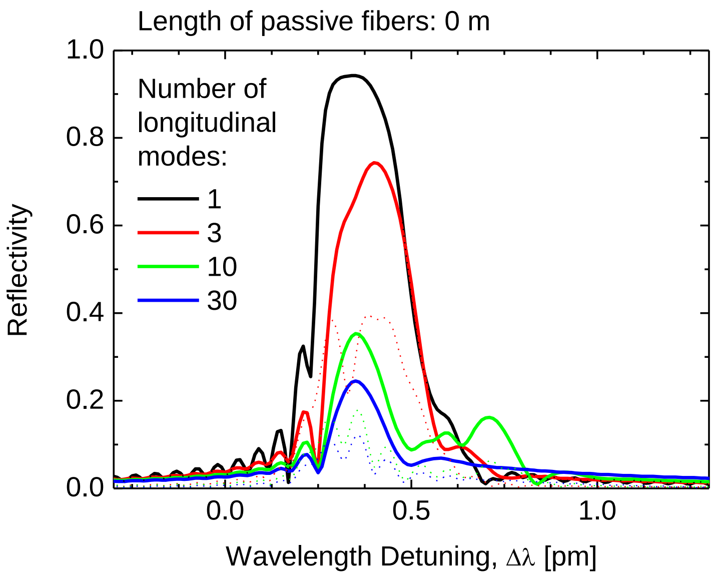


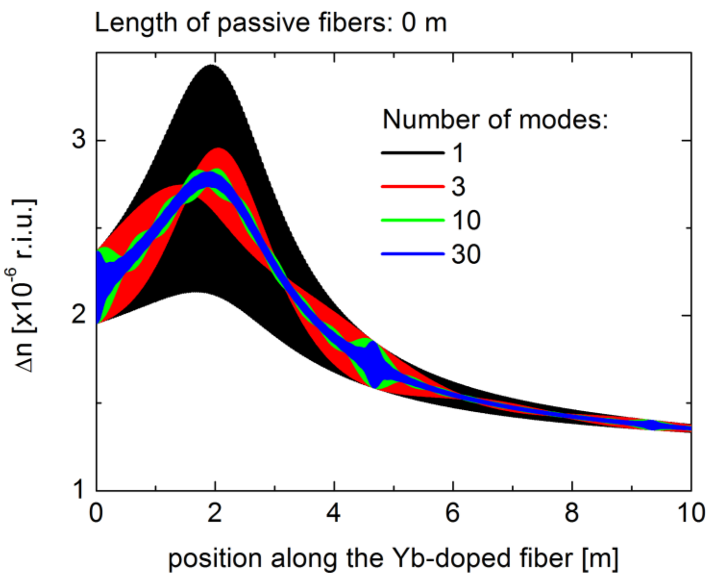




Reflectivity of FBGs in fiber laser without passive fibers







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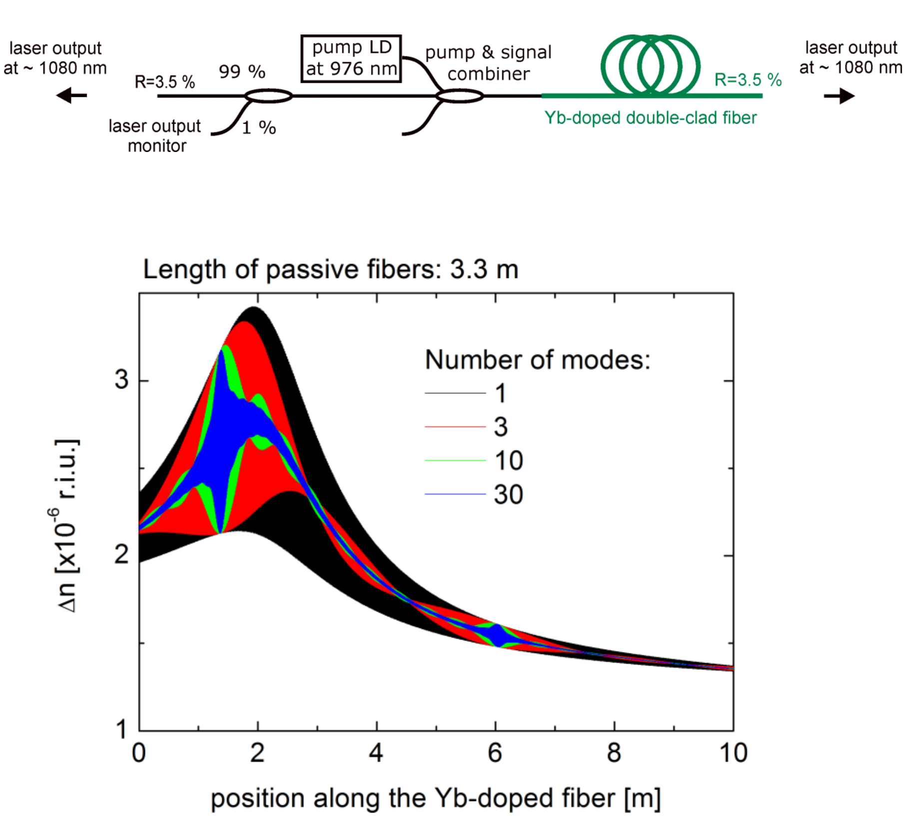
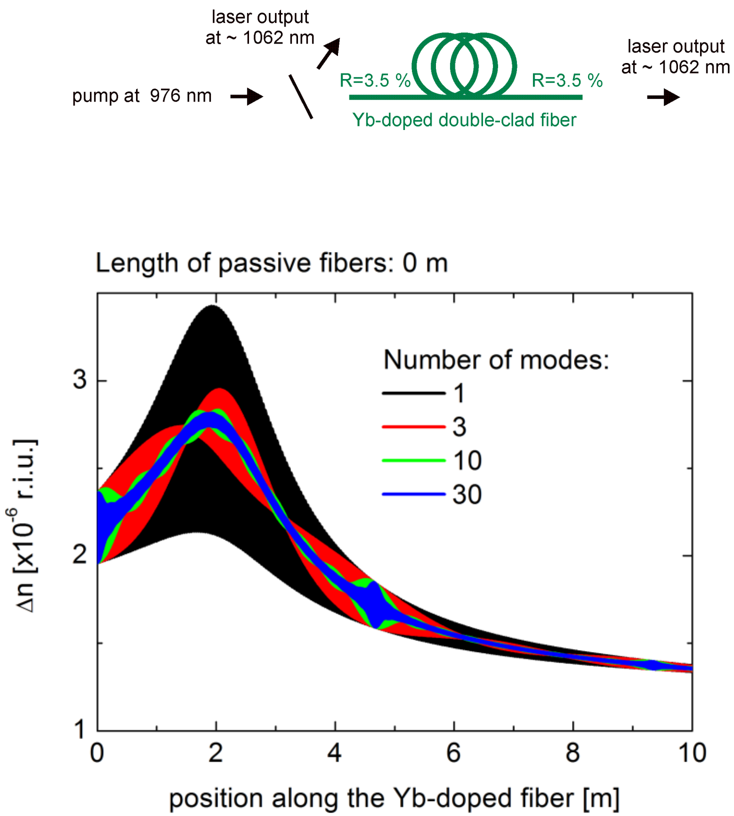
Length of the resonator determines the position of the interferogram





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Experimental verification

Reflectivity of transient FBG theoretical evaluation in 2014:

Peterka et al., OSA Adv. Photonics Congress 2014
Peterka et al., Opt. Express 2014

Reflectivity of transient FBG experimental measurement in 2016:

Lobach et al, Frontiers in Optics/Laser Science 2016

FTu2I.6.pdf Frontiers in Optics/Laser Science 2016 © OSA 2016

The Reflectivity Measurement of a Dynamically Formed Fiber Bragg Grating Inside an Yb-doped Fiber

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Abstract: Spatial hole burning in an active medium of a linear cavity Yb-doped fiber laser leads to formation of a dynamical fiber Bragg grating. Reflectivity of the grating (~5%) is measured for the first time.

OCIS codes: (060.3735) Fiber Bragg gratings; (060.3510) Lasers, fiber

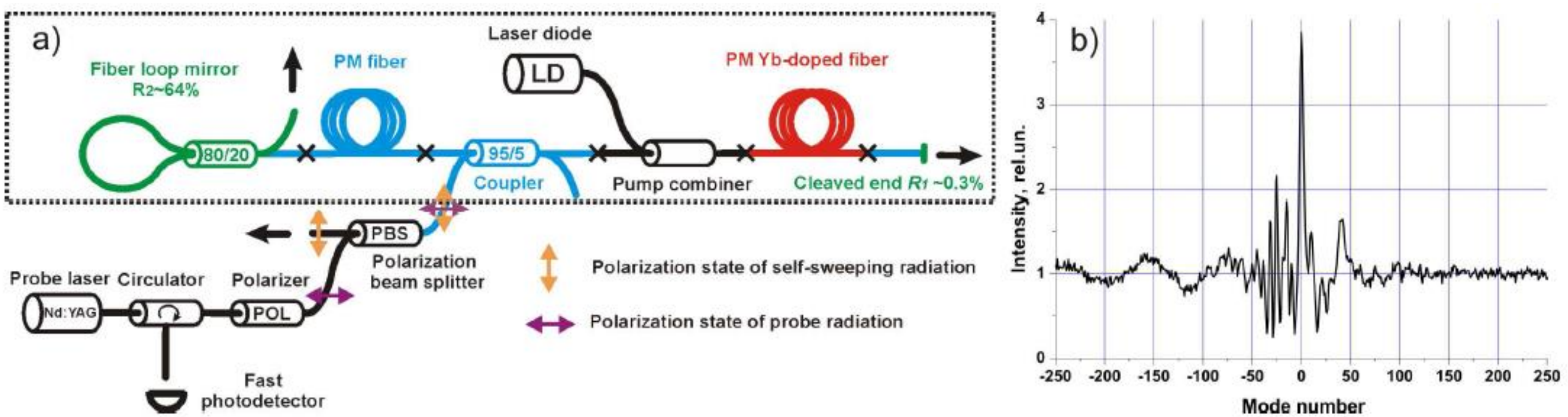


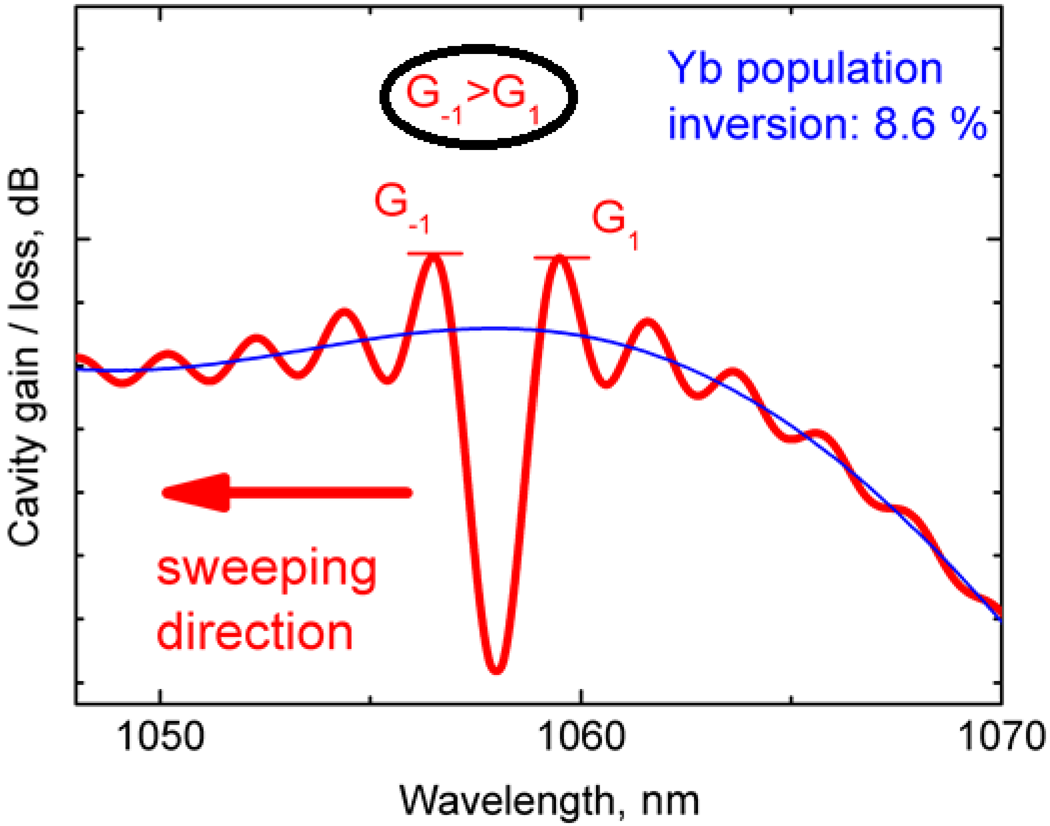
Fig. 1. (a) The experimental scheme for measurement of DFBG reflection in Yb-doped self-sweeping fiber laser (dashed rectangle). (b) The reflection spectrum for DFBG.

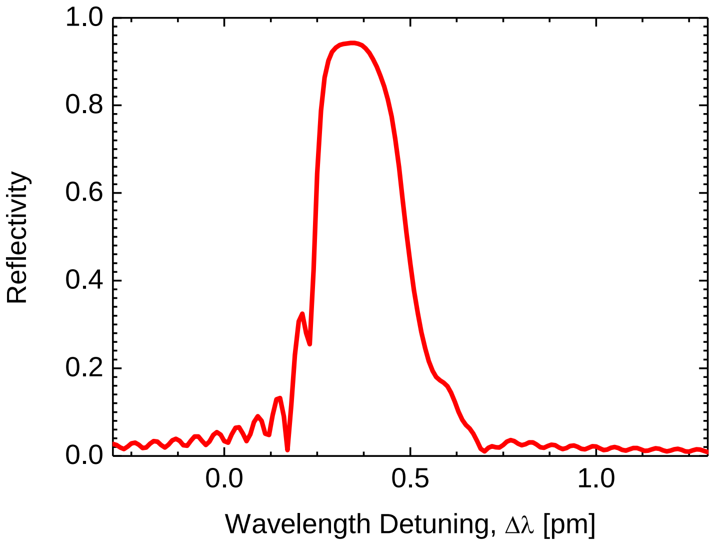
Conclusions

- We have reported evaluation of reflectivity of transient (dynamic) FBG spontaneously formed in the active medium in fiber lasers. New effect, not reported in laser physics before 2014.
- Multiple superimposed-damped-transient gratings were considered for the first time. Modification of the FBG model was derived.
- The reflectivity depend on the position of the max. interference fringes, for example on the lengths of passive fibers in the resonator.
- Future work: evaluation of the refractive index modification using time resolved model (possible shift of the max. reflectivity to shorter wavelengths) and for different pump wavelengths

Team of Fiber Lasers and Nonlinear Optics

Reverse sweeping



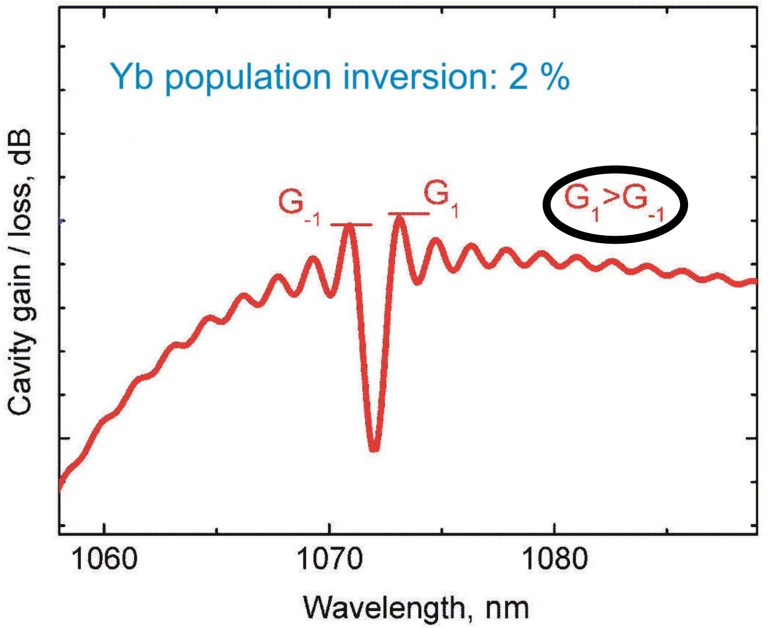


Reflectance of transient fiber Bragg grating may also affect the sweeping direction. The refractive index modulation is small but FBG is long → high R is possible. The reflectance is asymmetric.

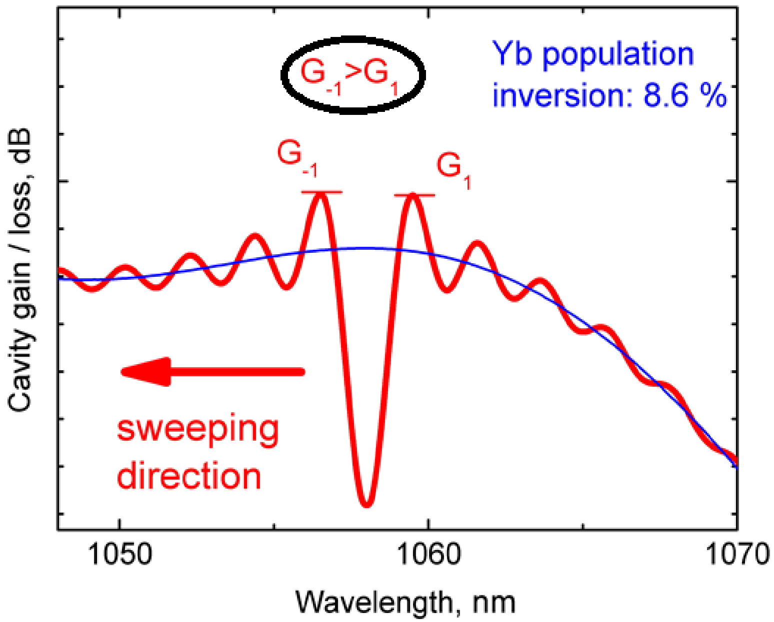
Peterka et al., Adv. Photonics Congress 2014, Opt. Express 2014 and 2016, Proc. SPIE 2015
Lobach et al., Laser Phys. Lett., 2014

Sweeping direction

Normal sweeping



Reverse sweeping



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