Conditions of single-mode light generation in DBR and DFB fiber lasers: wavelength-scale electromagnetic analysis by the method of single expression

Hovik Baghdasaryan[1], Tamara Knyazyan[1], Tamara Hovhannisyan[1], Marian Marciniak[2] , Erich Leitgeb[3], Sławomir Sujecki [4],Stefano Taccheo[5]

[1]*National Polytechnic University of Armenia, Yerevan, Armenia*
[2]*National Institute of Telecommunications, Warsaw, Poland*
[3]*Graz University of Technology, Graz, Austria*
[4]*The University of Nottingham, Nottingham, UK*
[5]*Swansea University, Swansea, United Kingdom*

E-mail: hovik@seua.am

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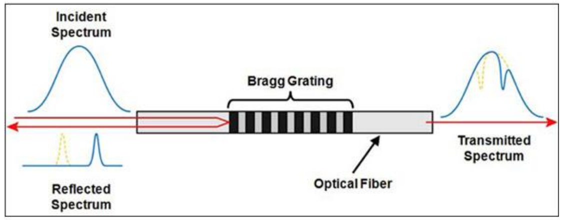
Fiber lasers consist of optically pumped amplifying fiber with fiber Bragg gratings (FBGs) as mirrors or as amplifying fiber Bragg gratings

http://activefibersystems.com/

Advantages of Fiber Lasers:

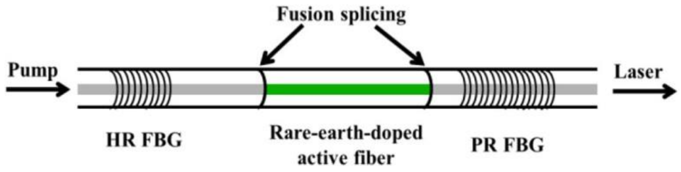
- High stability: spliced waveguiding fibers;
- High reliability;
- Low jitter and low amplitude noise;
- Compact form factor;
- Immunity to tough environmental changes.

Fiber Bragg grating (FBG) – in-fiber frequency selective mirror:



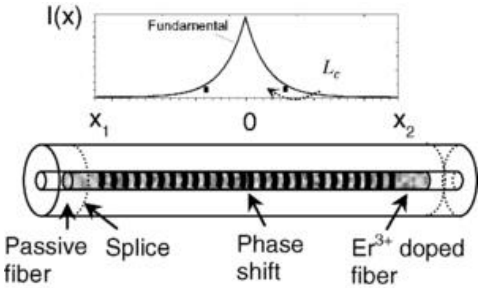
http://mydocs.epri.com/docs/CorporateDocuments/Newsletters/NUC/2010-09/09i.html

I. Distributed Bragg Reflector (DBR) fiber Lasers (FBG-amplifying fiber-FBG)



http://spie.org/x113867.xml

II. Distributed Feedback (DFB) fiber Lasers (FBG with π-phase shift)



http://iopscience.iop.org/article/10.1088/0957-0233/20/3/034023

Why we need single-frequency radiating fiber lasers?

There is a high need in following techniques:

- optical communication;
- interferometric sensing;
- coherent light detection;
- light ranging;
- laser spectroscopy, etc.

Single-mode fiber lasers operate with only one longitudinal mode, permitting emission of quasi-monochromatic radiation of very narrow linewidth and low noise.

Our goal is to find conditions of single-frequency radiation of DBR and DFB fiber lasers.

Modelling methods for analysis of fiber lasers' optical characteristics

Transfer matrix method,
Coupled-mode theory,
Finite-difference time-domain method,
Method of lines,
Beam propagation method

For fibers, the well known split-step Fourier method is often quite suitable.
A lot of phenomena can be investigated with numerical beam propagation method.

Unfortunately, simulation softwares often offer only 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 using the **method of single expression** (**MSE**), which takes into account contra directed waves summation without division on the forward and the backward propagating waves.

Concise description of the method of single expression (MSE)

$$\frac{d^2 \dot{E}_x(z)}{dz^2} + k_0^2 \dot{\varepsilon}(z)\, \dot{E}_x(z) = 0$$

where $\dot{\varepsilon}(z) = \varepsilon'(z) + j\varepsilon''(z)$

Helmholtz's equation

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

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

where $k = k_0 \sqrt{\dot{\varepsilon}(z)}$

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

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

This single expression describes resultant field amplitude and phase in a medium without division on counter-propagating waves. This approach permits to escape superposition principle application, that makes it favorable for solution of not only linear, but also nonlinear (intensity dependent) problems.

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.

H.V. Baghdasaryan and T.M. Knyazyan, "Simulation of Amplifying Phase-Shifted Bragg Gratings by the Method of Single Expression", Optical and Quantum Electronics, vol. 35, No. 4, 2003, pp.493 - 506.

Algorithm of boundary problem solution in the MSE

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

1. Presentation of Helmholtz equation in terms of variables U(z) and S(z):

$$\begin{cases} \dfrac{dU(z)}{d(k_0 z)} = Y(z) \\ \dfrac{dY(z)}{d(k_0 z)} = \dfrac{P^2(z)}{U^3(z)} - \varepsilon'(z)\cdot U(z) \\ \dfrac{dP(z)}{d(k_0 z)} = \varepsilon''(z)\cdot U^2(z), \end{cases}$$

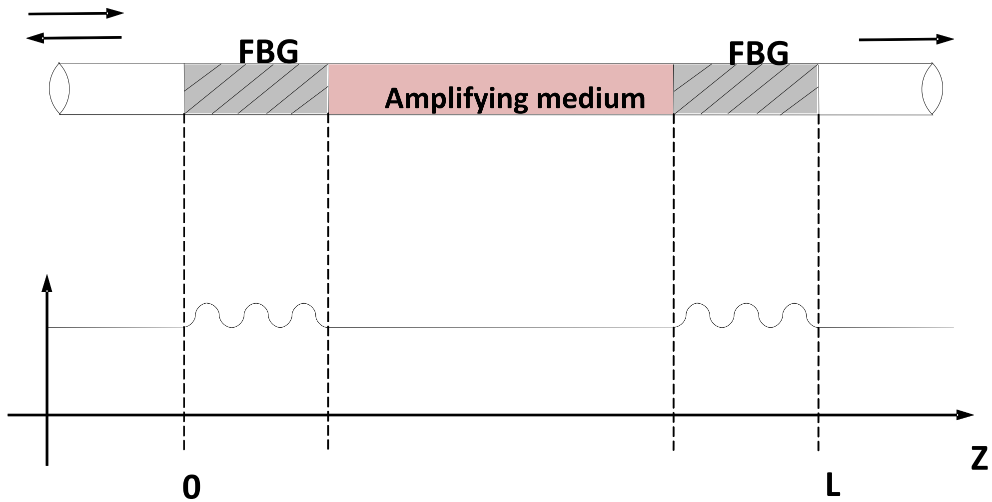
$$P(z) = U^2(z)\frac{dS(z)}{d(k_0 z)}$$ - value proportional to the Poynting vector.

2. Matching of boundary conditions of electrodynamics at the interfaces;

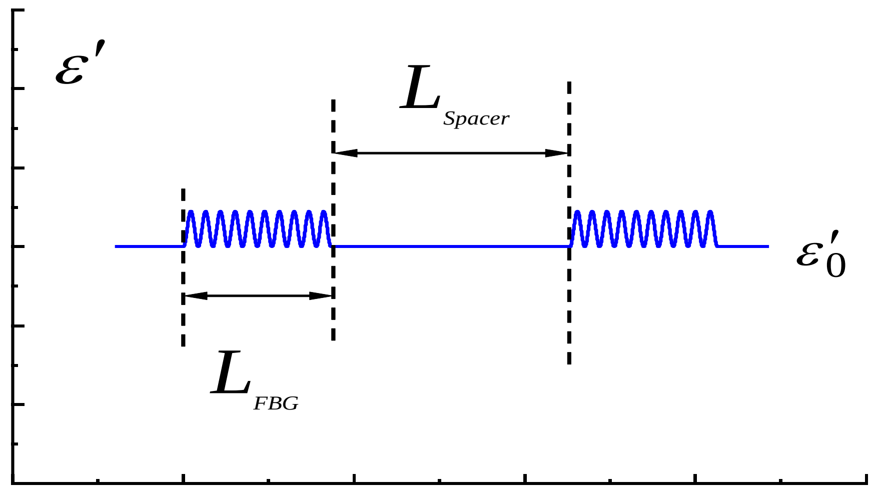
3. Backward calculation (via Runge-Kutta method). Start from the output.

DBR fiber laser (FBG-fiber-FBG) structure under analysis

Schematic view:

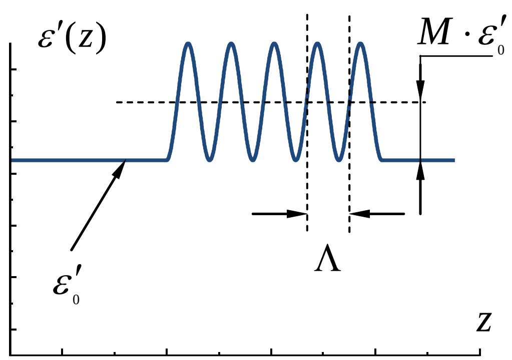


Permittivity profile of the structure:



Single sinusoidal fiber Bragg grating (FBG)

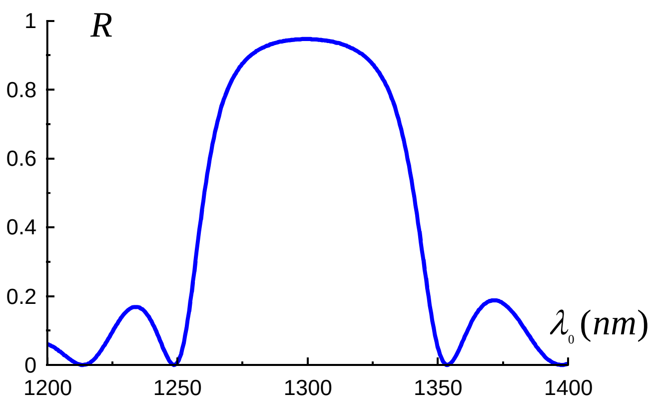
Permittivity profile of FBG:



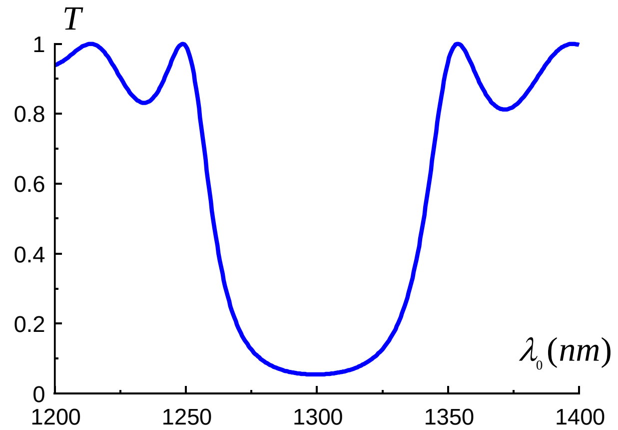
$$\varepsilon'_{FBG} = \varepsilon'_0 \cdot (1 + M + M \cdot \cos(2\pi \frac{z}{\Lambda}))$$

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

Reflection spectrum: $\lambda_{0Br} = 1300$ nm



Transmission spectrum:



Number of periods: $N = 30$

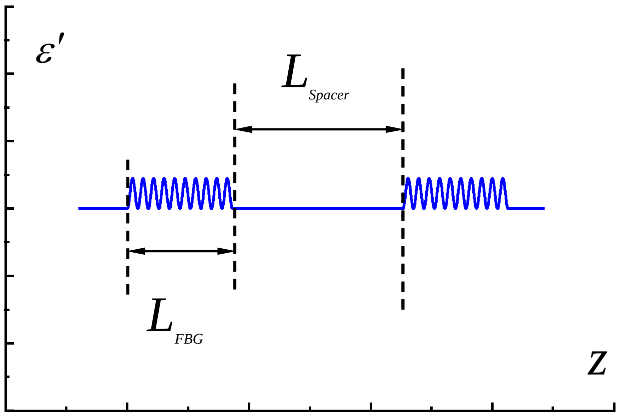
$\Lambda = 413.167$ nm

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

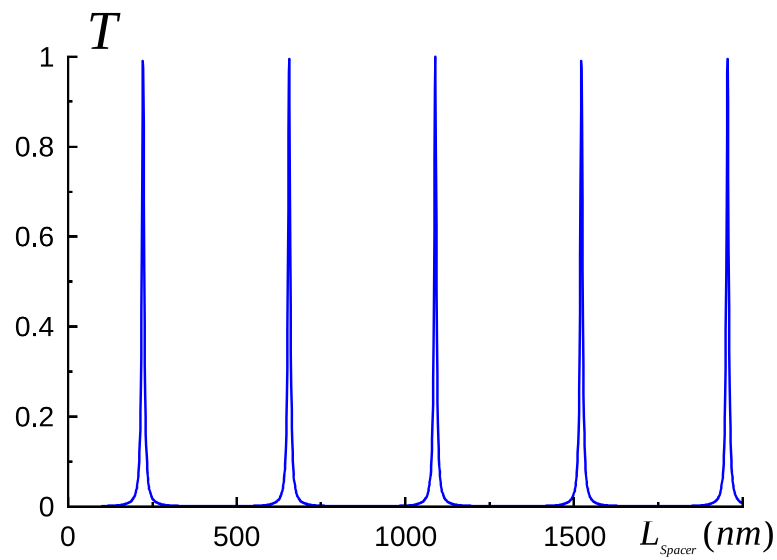
$L_{FBG} = 30 \times \Lambda = 12395.01$ nm

Transmission spectrum of DBR fiber laser structure at FBG mirrors' Bragg wavelength

Permittivity profile:



Transmittance of FBG-Spacer-FBG structure from the length of the spacer, at $\lambda_0 = \lambda_{0Br} = 1300$ nm



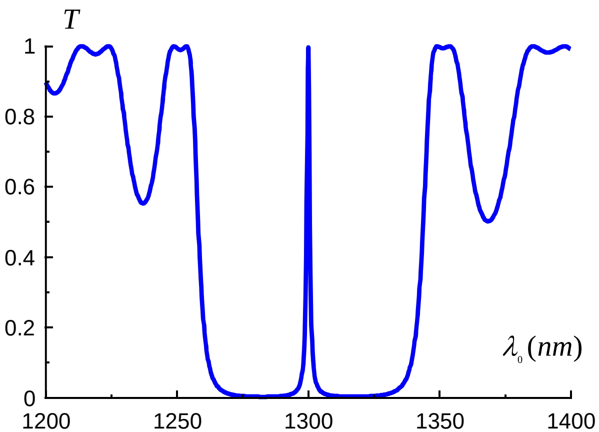
Full transmissions are observed at **resonant lengths** of the spacer (no loss, no gain is assumed in the structure):

$$L_{Spacer} = m \cdot \frac{\lambda_{0Br}}{2\sqrt{\varepsilon_{Spacer}}} + \frac{\lambda_{0Br}}{3.9\sqrt{\varepsilon_{Spacer}}}, \quad m = 0,1,2,3\ldots\ .$$

Single-frequency radiation is observed at these resonant lengths of the spacer!

Transmittances of DBR fiber laser (FBG-spacer –FBG) structure at resonant lengths of spacer

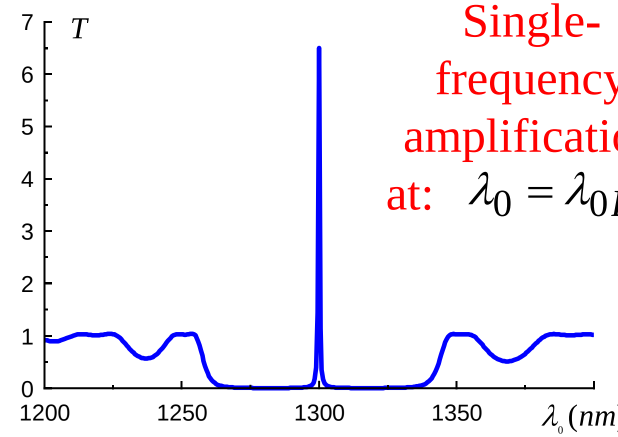
without $\varepsilon'' = 0$ and with amplification $\varepsilon'' > 0$ in the spacer:



At $\varepsilon'' = 0$

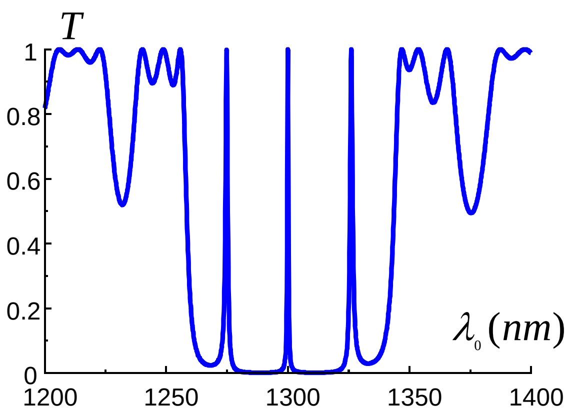
$L_{Spacer} = 1955.5$ nm

$L_{spacer} < L_{FBG}$



$\varepsilon'' = 0.005$

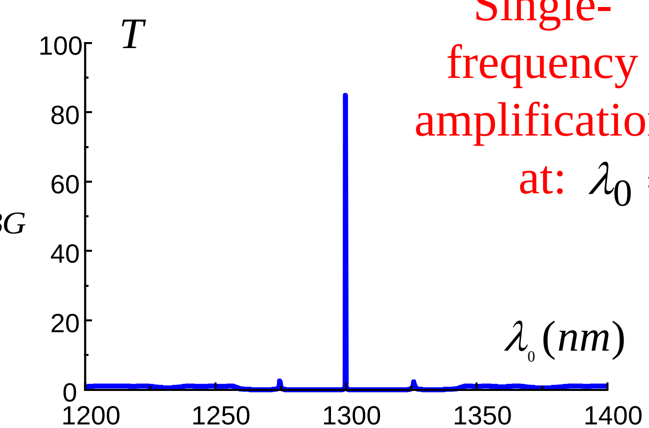
Single-frequency amplification at: $\lambda_0 = \lambda_{0Br}$



At $\varepsilon'' = 0$

$L_{Spacer} = 15389$ nm

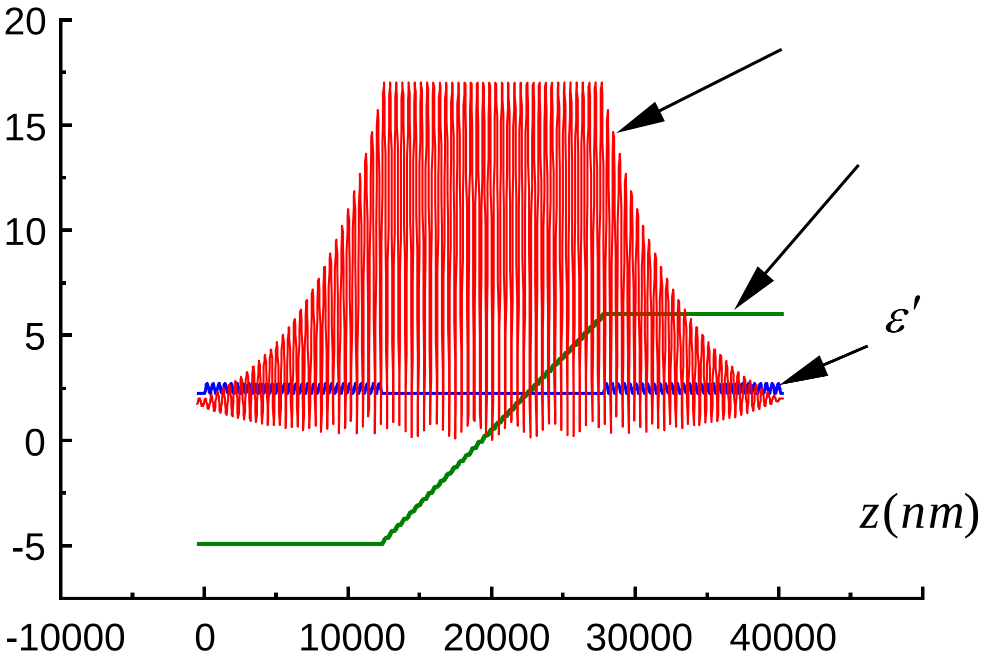
$L_{FBG} < L_{spacer} < 2L_{FBG}$

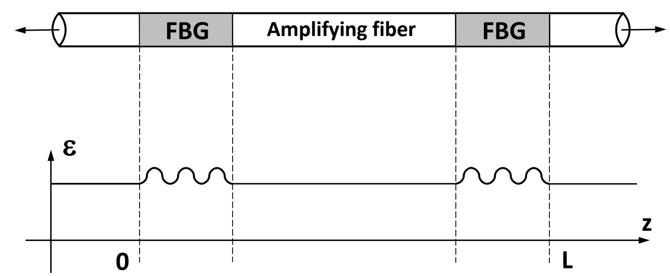


$\varepsilon'' = 0.001$

Single-frequency amplification at: $\lambda_0 = \lambda_{0Br}$

Distributions of electric field amplitude E and Poynting vector P in a lasing structure at $\lambda_0 = \lambda_{0Br}$



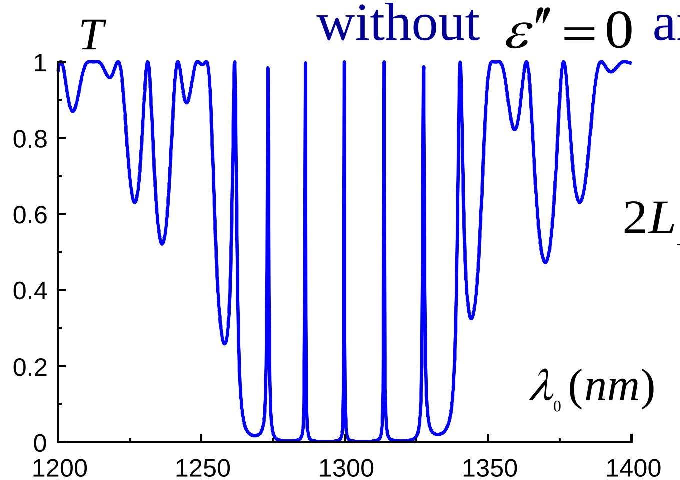


Distributions of electric field amplitude $\hat{E}$, Poynting vector P and permittivity profile $\varepsilon'(z)$ at Bragg wavelength of lasing structure. $\varepsilon'' = 0.0015$

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

Transmittance of DBR fiber laser (FBG-spacer –FBG) structure at the resonant length of spacer

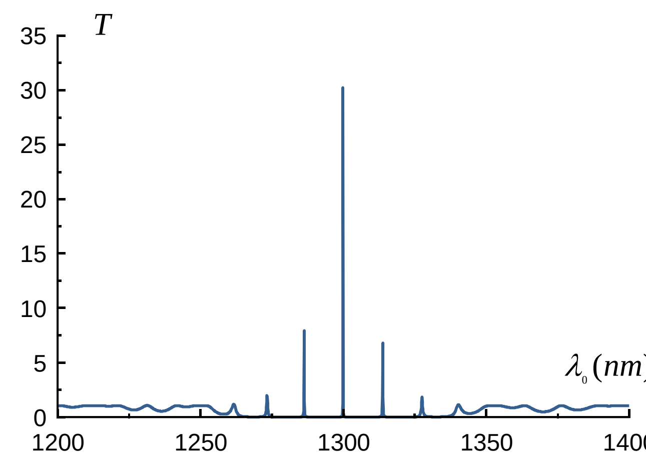
without $\varepsilon'' = 0$ and with amplification $\varepsilon'' > 0$ in the spacer



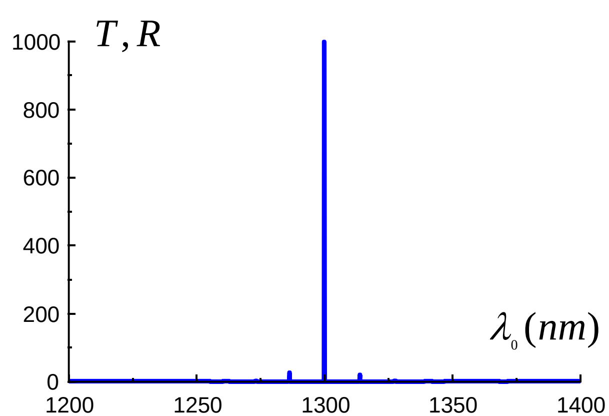
$\varepsilon'' = 0$

$L_{Spacer} = 34886$ nm

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



$\varepsilon'' = 0.0004$



$\varepsilon'' = 0.0005$

Single- frequency radiation (lasing) at:

$\lambda_0 = \lambda_{0Br}$

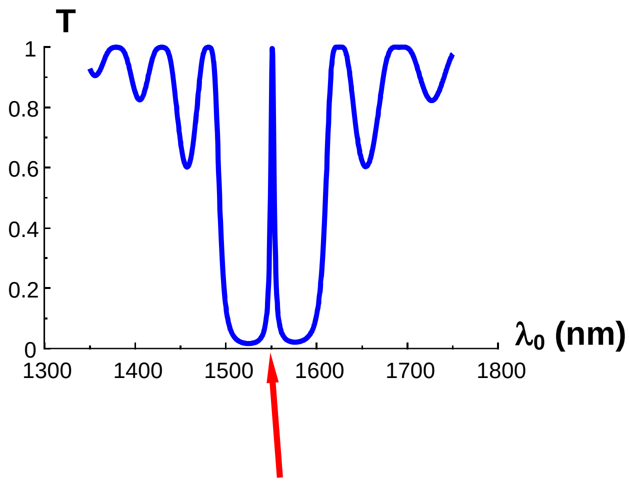
CONCLUSION:

- For single-frequency lasing of DBR fiber laser the length of an amplifying fiber is determined correctly via wavelength-scale numerical modelling by the MSE.
- At the resonant lengths of an amplifying spacer between FBG mirrors only one radiating peak is survived. This phenomenon is elucidated by the analysis of field distribution inside the structure.
- Thus, by proper choice of the length of an amplifying fiber spacer it is possible to have single-frequency radiation from DBR fiber laser.

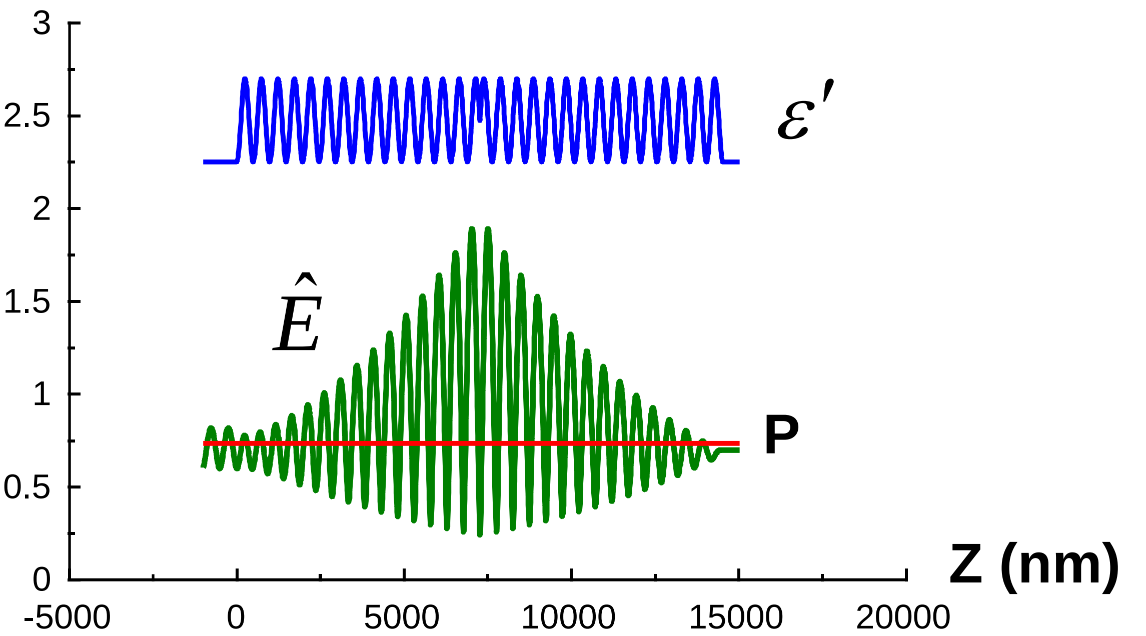
Modelling of DFB fiber laser

Gainless sinusoidal π-phase-shifted FBG $\varepsilon'' = 0$

The distributions of the electric field amplitude and the power flow density in a gainless π-phase-shifted FBG:



$$\lambda_{0Br} = 1550\,\text{nm}$$



$$\varepsilon'_0 = 2.25 \qquad M = 0.1$$

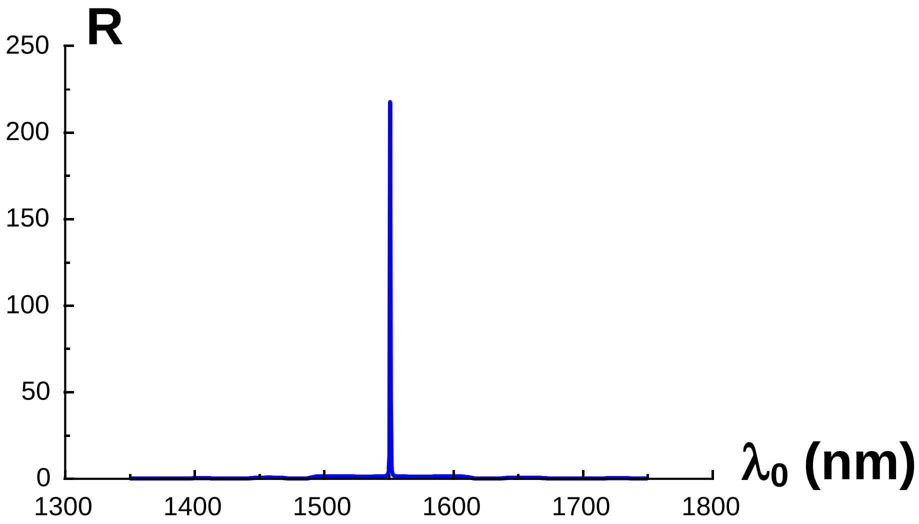
$$L_1 / \Lambda = L_2 / \Lambda = 25$$

$$L_{FBG} = L_1 + L_2$$

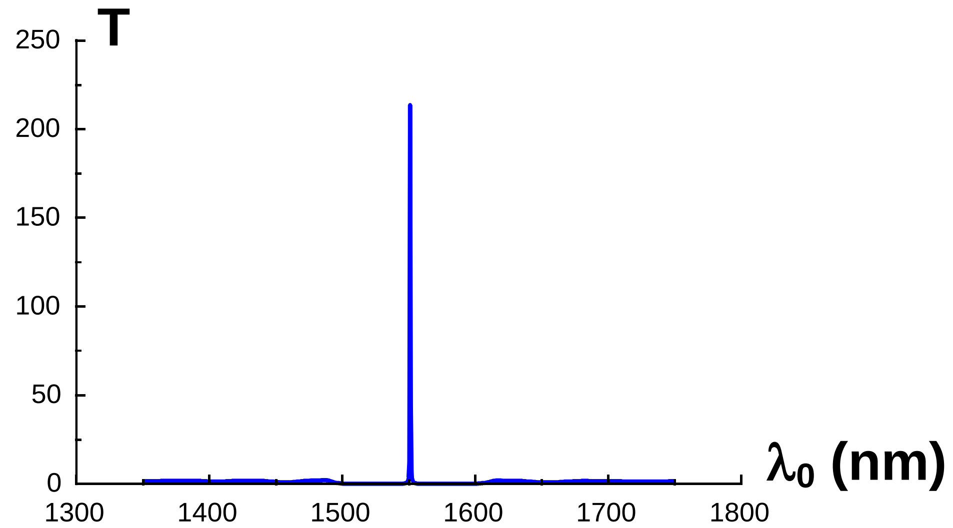
Modelling of DFB fiber laser

Gainy sinusoidal π-phase-shifted FBG $\varepsilon'' = 0.007$

Reflection spectrum



Transmission spectrum



$$\lambda_{0Br} = 1550\,\text{nm}$$

$$\varepsilon_0' = 2.25 \qquad M = 0.1$$

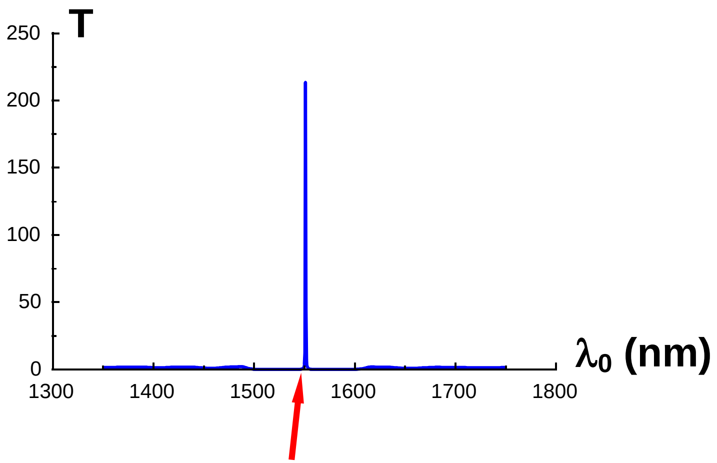
$$L_1 / \Lambda = L_2 / \Lambda = 25$$

Single-frequency radiation at $\lambda_{0Br} = 1550\,\text{nm}$

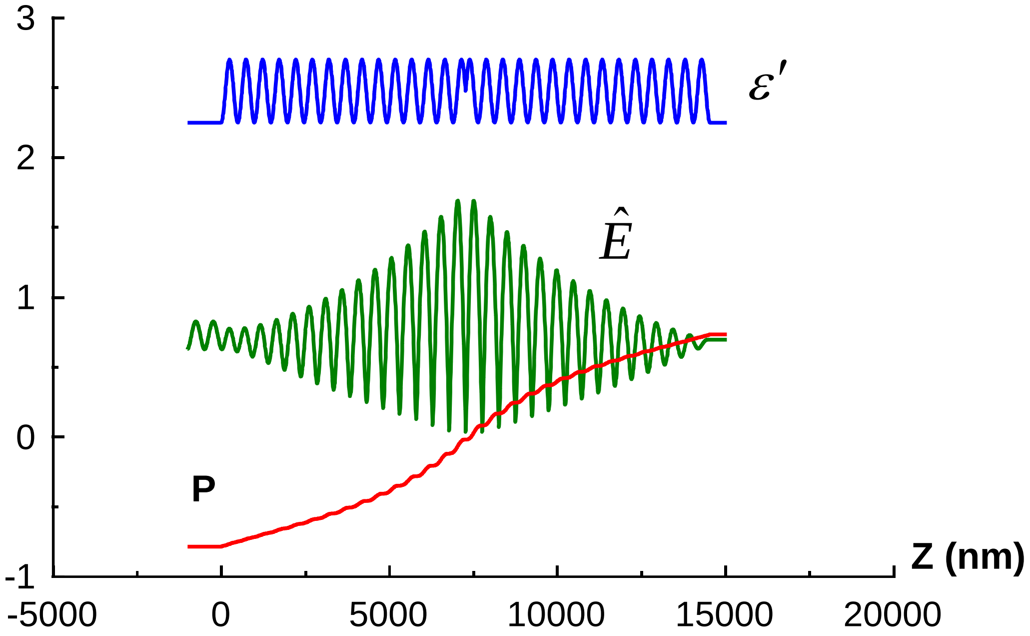
$$L_{FBG} = L_1 + L_2$$

Modelling of DFB fiber laser

The distributions of the electric field amplitude and the power flow density in a gainy π-phase-shifted FBG $\varepsilon'' = 0.035$



$\lambda_{0Br} = 1550\text{nm}$



$\varepsilon_0' = 2.25$ $M = 0.1$

$L_1 / \Lambda = L_2 / \Lambda = 15$

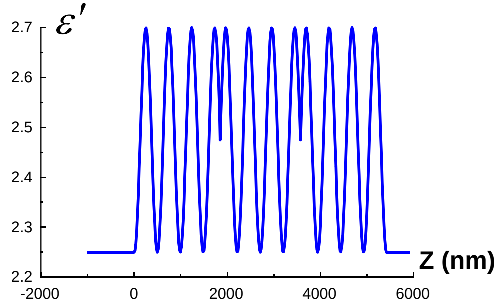
Single-frequency radiation at $\lambda_{0Br} = 1550\text{nm}$

$L_{FBG} = L_1 + L_2$

Modelling of DFB fiber laser

Gainless sinusoidal FBG with equally spaced two π-phase-shifts

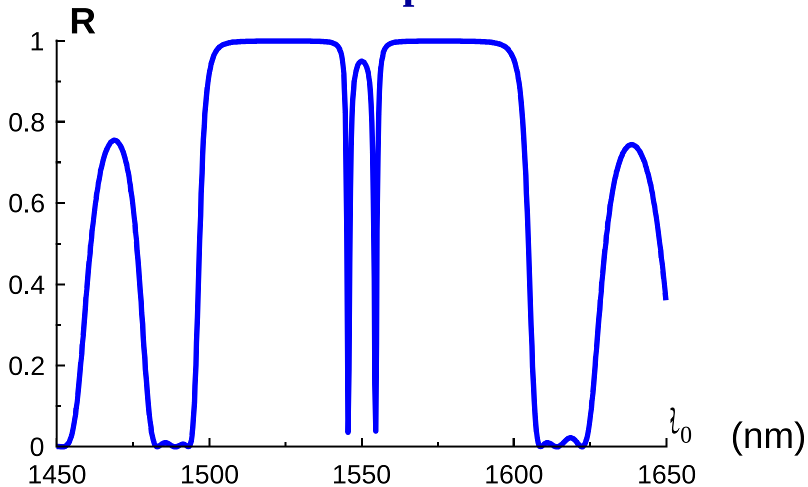
$$\varepsilon'' = 0$$



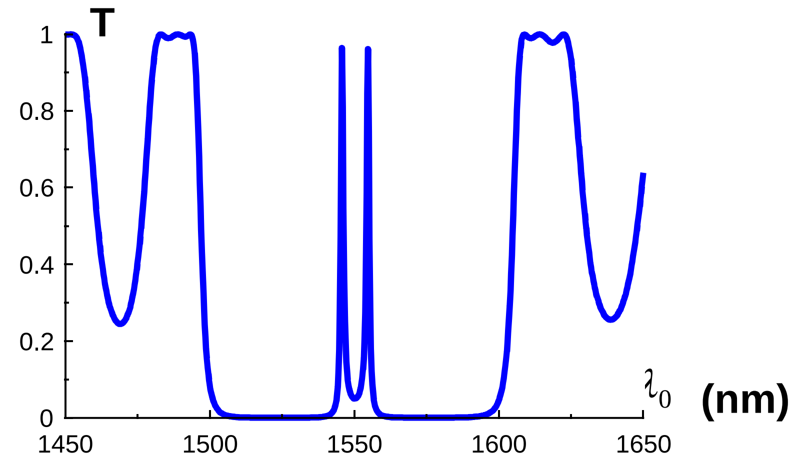
$$L_1/\Lambda = L_2/\Lambda = L_3/\Lambda = 4$$

$$L_{FBG} = L_1 + L_2 + L_3$$

Reflection spectrum



Transmission spectrum

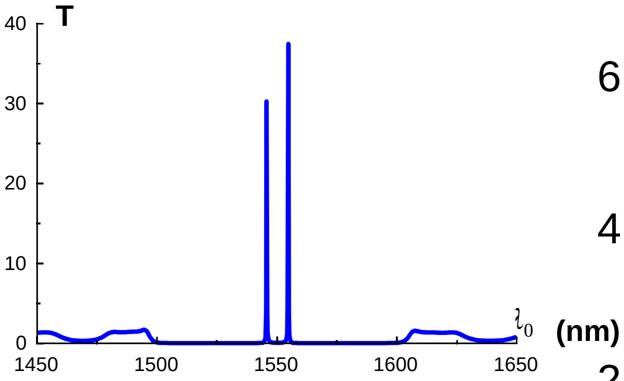


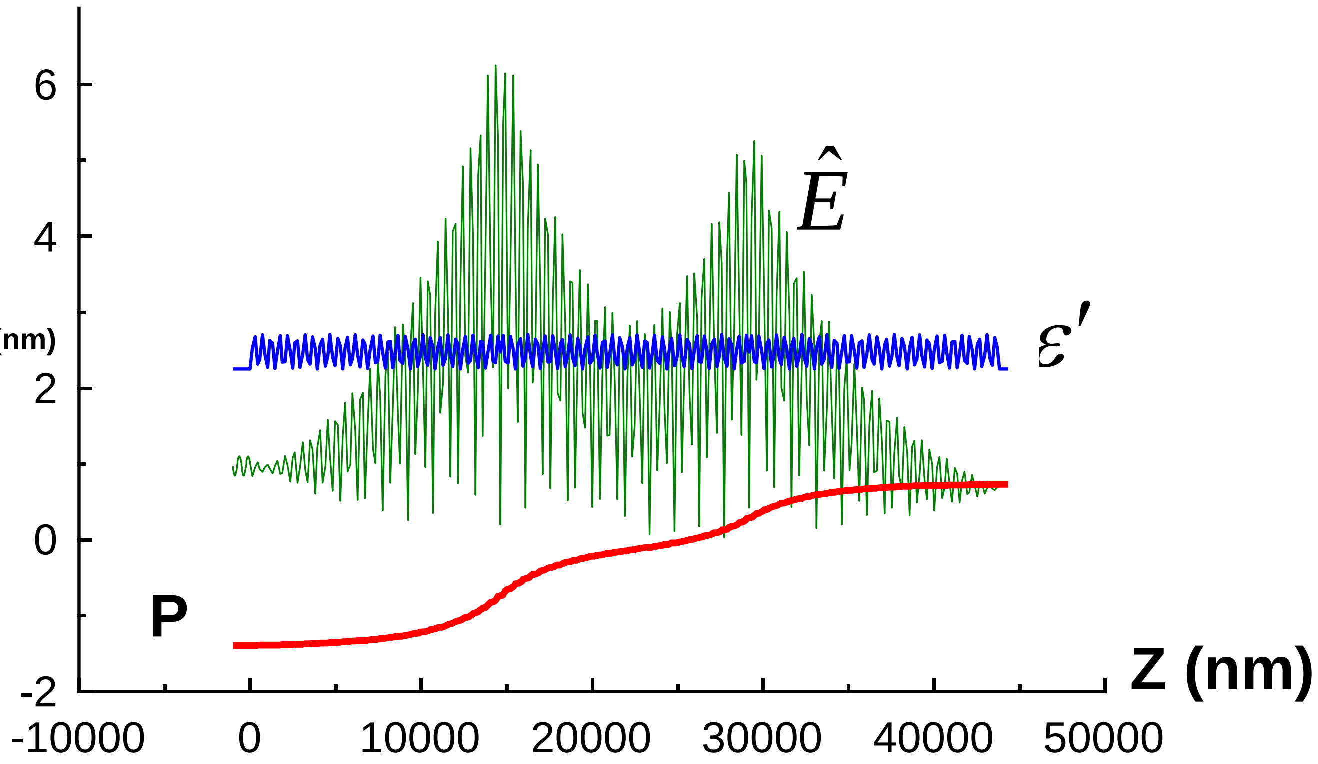
$$\lambda_{0Br} = 1550\text{nm} \quad \varepsilon_0' = 2.25 \quad M = 0.1$$

$$L_1/\Lambda = L_2/\Lambda = L_3/\Lambda = 30 \qquad L_{FBG} = L_1 + L_2 + L_3$$

Modelling of DFB fiber laser

The distributions of the electric field amplitude and the power flow density in a gainy FBG with equally spaced two π-phase-shifts





$$\lambda_{0Br} = 1550\,\text{nm}$$

$$\varepsilon'' = 0.002$$

$$\varepsilon_0' = 2.25 \qquad M = 0.1$$

$$L_1/\Lambda = L_2/\Lambda = L_3/\Lambda = 30$$

Conclusions

- Optical properties of DFB fiber lasers have been analyzed through detailed wavelength-scale electrodynamical modelling by the MSE to reveal advantageous configurations for efficient single-mode radiation emission.
- Inclusion of gain in the π-phase-shifted FBG results in an essential narrowing and enhancing of the transmission peak in the middle of the stop-band of the corresponding uniform FBG.
- In the π-phase-shifted DFB laser a high resonant field distribution is observed in the middle of the structure which is favourable for efficient single-mode radiation. Power flow density with positive value in the right part of the structure and negative – in the left side of it, clearly indicates on radiation from both sides of the single-mode DFB laser.
- Introduction of two π-phase-shifts in the structure of the uniform FBG brings to the appearance of the two closely located reflection minima (transmission maxima) at both sides of the central Bragg wavelength. Inclusion of gain of sufficient value in such structure converts a single-mode DFB laser into a dual-wavelength DFB laser.

Thank you for attention!

Yerevan, capital of Armenia