Wavelength-scale Electrodynamical Modelling of Optical Characteristics of DFB Fiber Laser by the Method of Single Expression

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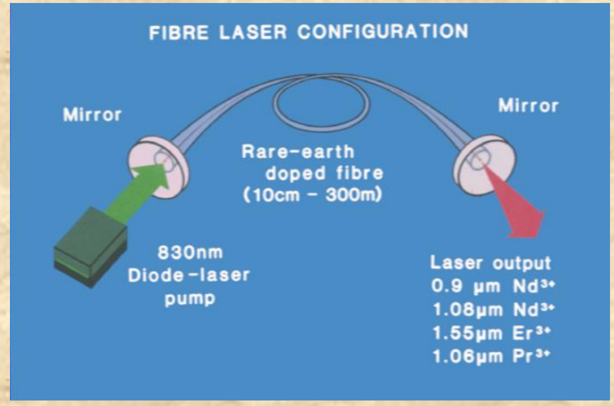
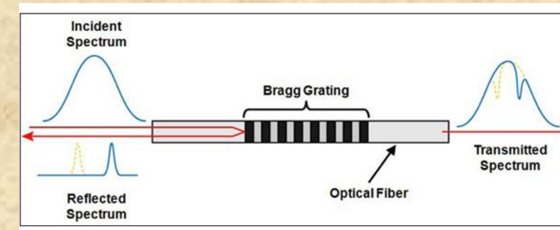
Outline of the presentation:

- **Introduction to Single-mode Fiber Lasers**
- **Modelling Methods and Approaches for the Analysis of Single-mode Fiber Lasers**
- **Method of Single Expression (MSE)**
- **Results of Numerical Modelling of DFB Fiber Laser by the MSE**
- **Discussion**
- **Conclusions**

Types of single-mode fiber lasers

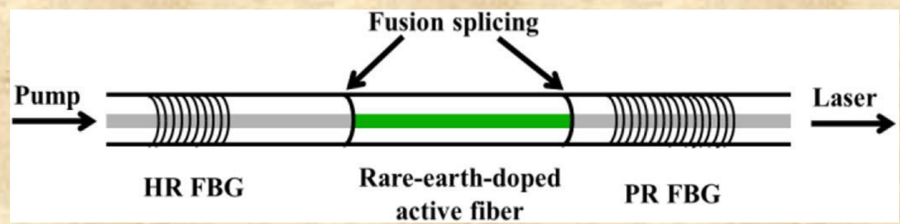


https://www.keopsys.com/portfolio/
cw-ytterbium-fiber-laser-kilo-series/



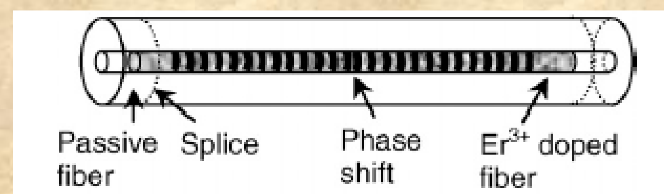
http://mydocs.epri.com/docs/CorporateDocuments/Newsletters/NUC/2010-09/09i.html

Fiber Lasers with Distributed Bragg Gratings - DBR fiber lasers



http://spie.org/x113867.xml

Distributed Feedback Fiber Lasers - DFB fiber lasers



http://dx.doi.org/10.1088/0957-0233/20/3/034023

The advantages of using single-mode DFB fiber lasers

- better single-frequency stability free from undesirable mode-hopping phenomenon;
- narrow linewidth;
- low noise performance;
- better coupling into a single-mode optical fiber;
- electromagnetic-radiation immunity;
- reliability;
- suitable power outputs range from several milliwatts to tens of milliwatts;
- seeding in high power lasers;
- comparative simplicity and compactness with a length of a few millimeters or centimeters.

The applications of DFB fiber lasers:

- optical communication;
- sensing;
- remote measurements;
- spectroscopy;
- medicine;
- military science, etc.

Single-mode fiber lasers operate at 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 DFB fiber lasers!

Modelling methods for 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. **Beam propagation method** is the most efficient. A lot of phenomena can be investigated with the numerical beam propagation method.

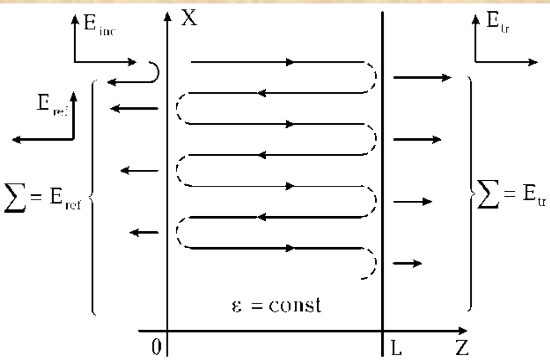
Unfortunately, simulation softwares often offer only single-pass propagation, but not the calculation of self-consistent steady-state solutions for lasers.

Dr. Rüdiger Paschotta

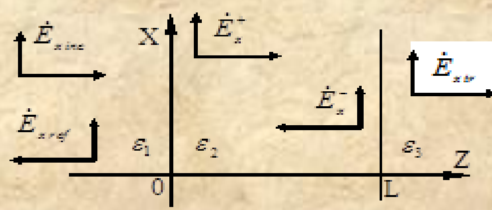
https://www.rp-photonics.com/tutorial_modeling3.html

For a self-consistent steady-state numerical modelling we are using the **method of single expression (MSE)**, which takes into account a propagation of contra directed waves without division on the forward and the backward propagating waves.

Main approaches in the solution of boundary problems of electrodynamics



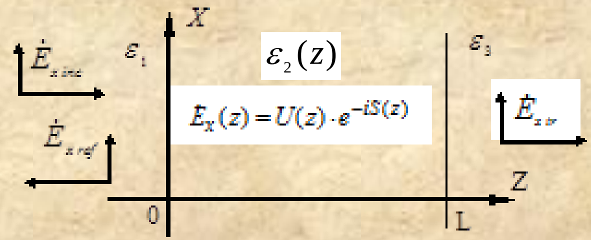
1. **Method of multiple reflections** - suitable for single and two layers problem, but **not** applicable for multilayer structures;



2. **Method of resultant waves** - suitable for multilayer structures, but **cannot** be used for nonlinear layers treatment by the reason of superposition principle application;

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

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



3. **Method of single expression** - suitable for both linear and nonlinear multi-boundary problems solution by the reason of avoiding superposition principle.

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

BASICS OF THE METHOD OF SINGLE EXPRESSION (MSE)

Helmholtz's equation for a medium with complex permittivity $\tilde{\varepsilon} = \varepsilon' + i\varepsilon''$

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

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

resultant electric field amplitude

resultant phase

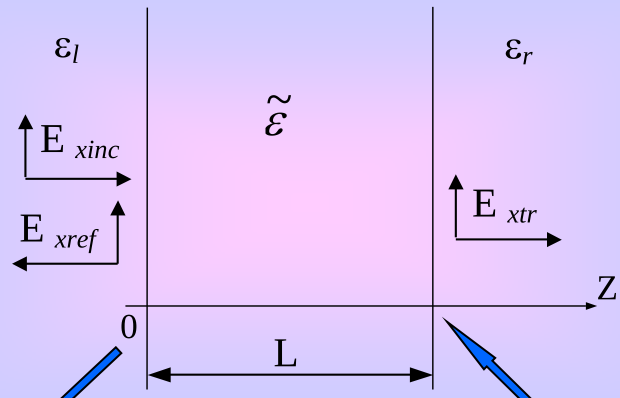
Helmholtz's equation in the terms of the **MSE**

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

$$P(z) = U^2(z) \frac{dS(z)}{d(k_0 z)}$$

quantity proportional to the **power flow density (Poynting vector)**

Boundary value problem in the terms of the **MSE**



$$E_{xinc} = \left| \frac{U^2(0) \cdot \sqrt{\varepsilon_l} + P(0) + iU(0) \cdot Y(0)}{2U(0) \cdot \sqrt{\varepsilon_l}} \right|$$

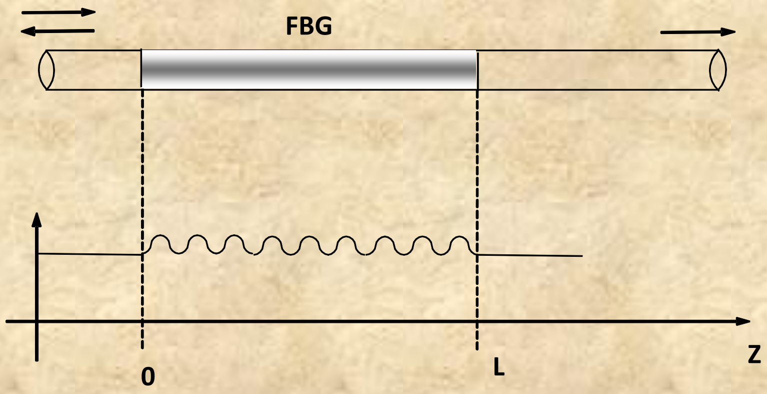
$$r = \frac{E_{xref}}{E_{xinc}} = \frac{U^2(0) \cdot \sqrt{\varepsilon_l} - P(0) - iU(0) \cdot Y(0)}{U^2(0) \cdot \sqrt{\varepsilon_l} + P(0) + iU(0) \cdot Y(0)}$$

$$T = t^2 = \frac{\sqrt{\varepsilon_r} \cdot E_{xtr}^2}{\sqrt{\varepsilon_l} \cdot E_{xinc}^2}$$

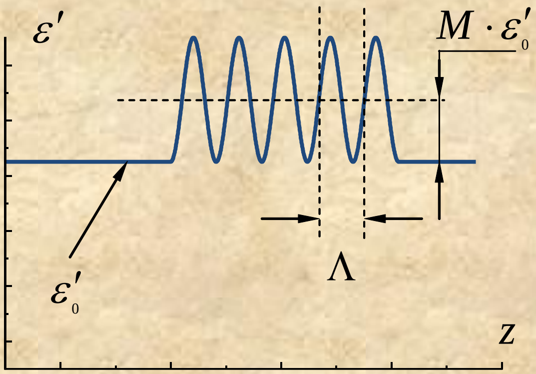
$$U(L) = E_{tr}, \quad Y(L) = 0, \quad P(L) = E_{tr}^2 \cdot \sqrt{\varepsilon_r}$$

Modelling of DFB fiber laser

Schematic view:



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

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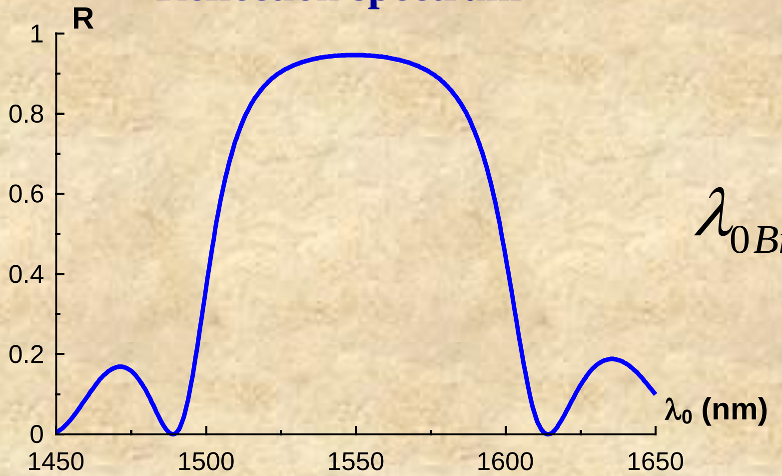
Modelling of DFB fiber laser

Gainless single sinusoidal fiber Bragg grating (FBG)

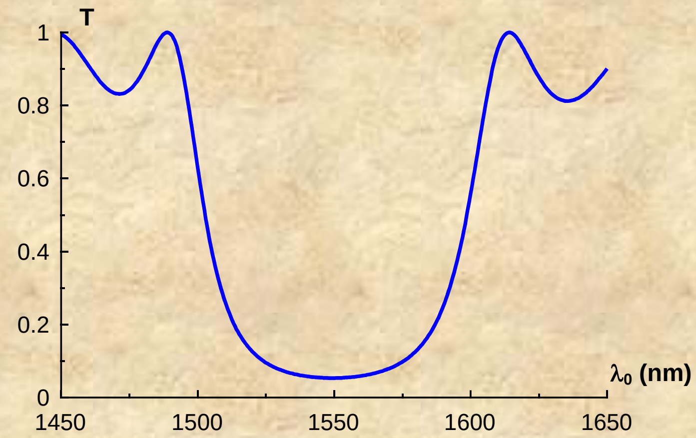
$$\varepsilon'' = 0$$

Reflection spectrum



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

Transmission spectrum



$$L/\Lambda = 30$$

L **is the grating length**

$$\Lambda = 492.626 \text{ nm}$$

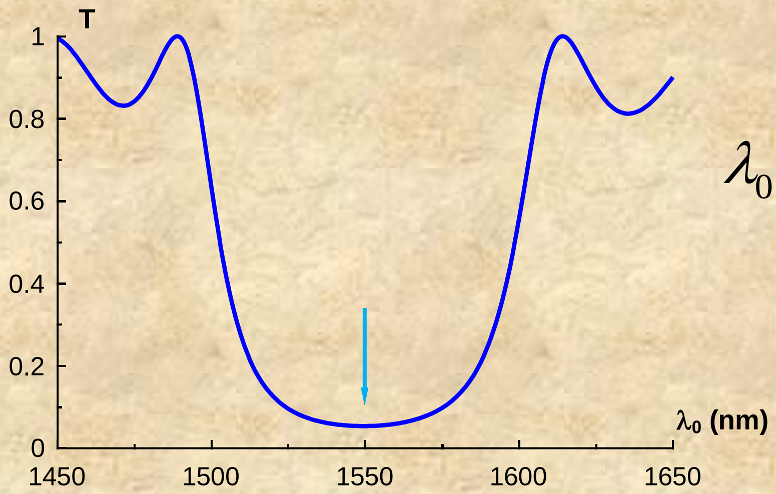
$$L_{FBG} = 30 \times \Lambda = 14778.78 \text{ nm}$$

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

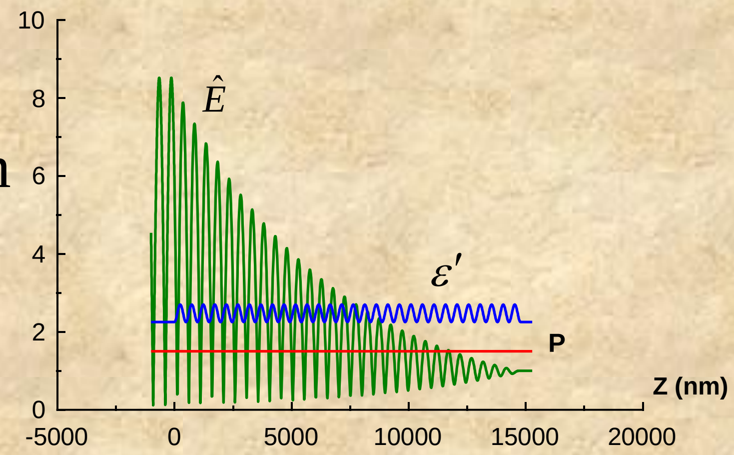
Modelling of DFB fiber laser

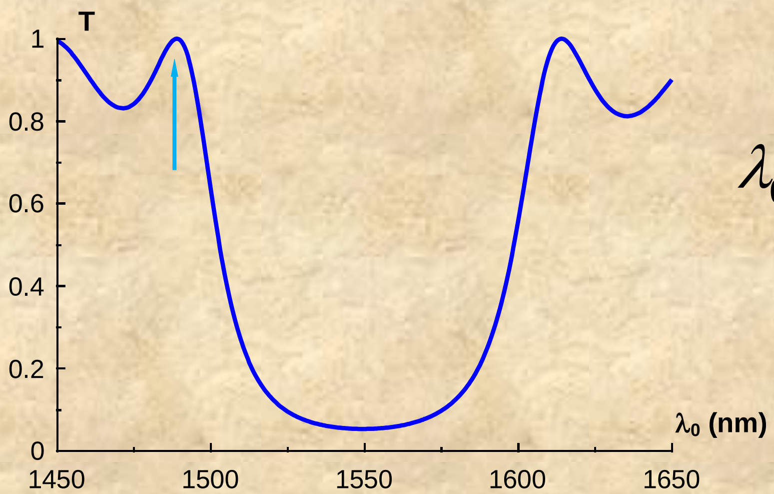
The distributions of the electric field amplitude and the power flow density in a gainless single FBG

$$\varepsilon'' = 0$$

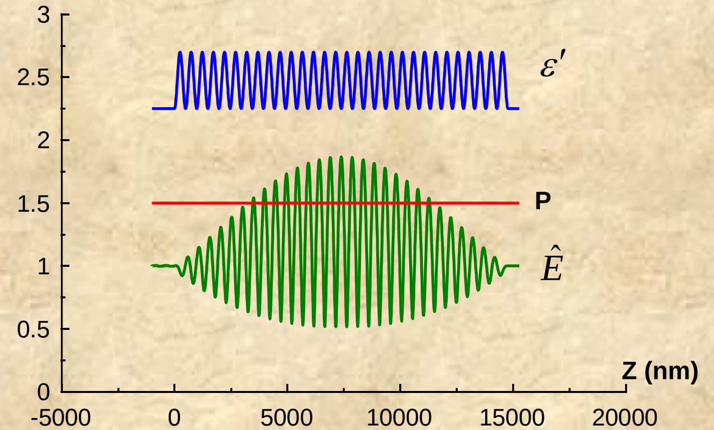


$$\lambda_{0Br} = 1550\,\text{nm}$$





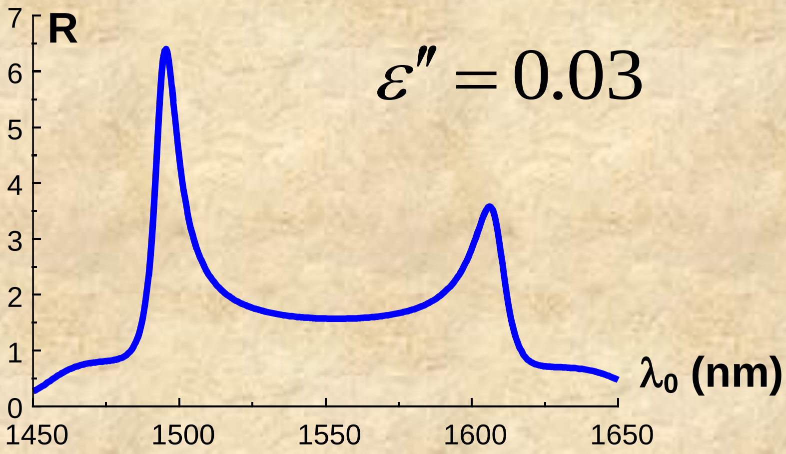
$$\lambda_0 = 1489\,\text{nm}$$

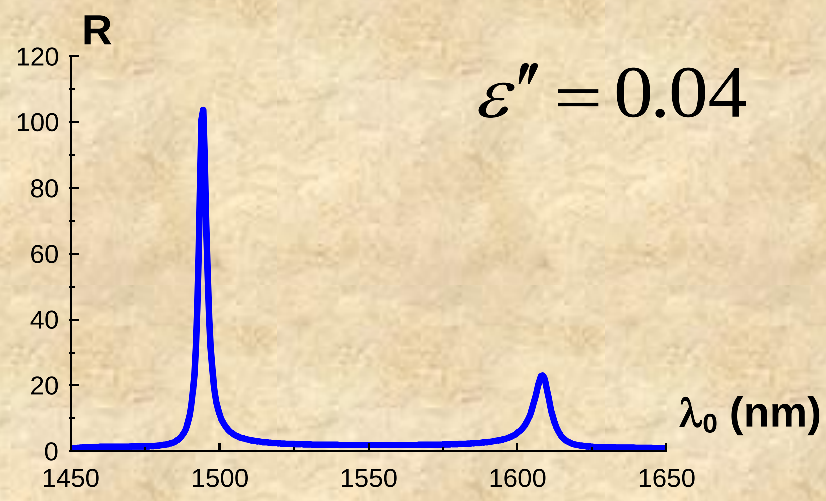


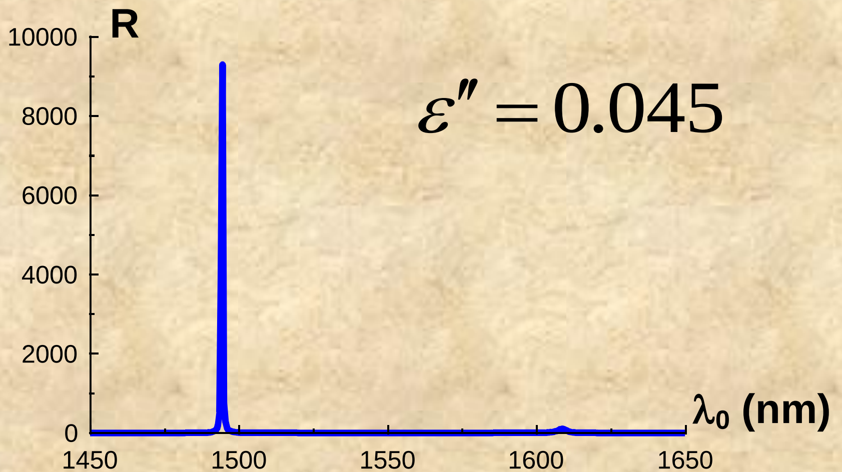
Modelling of DFB fiber laser

Gainy single sinusoidal FBG

Reflection spectra for different values of gain $\varepsilon'' > 0$







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

$$L/\Lambda = 30 \quad M = 0.1$$

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Modelling of DFB fiber laser

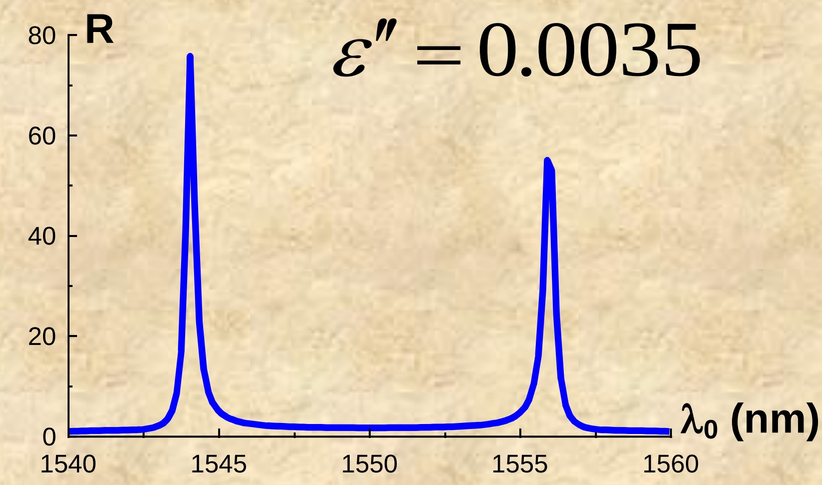
Gainy single sinusoidal FBG of a greater length and a lower modulation amplitude

Reflection spectra of gainless and gainy FBGs

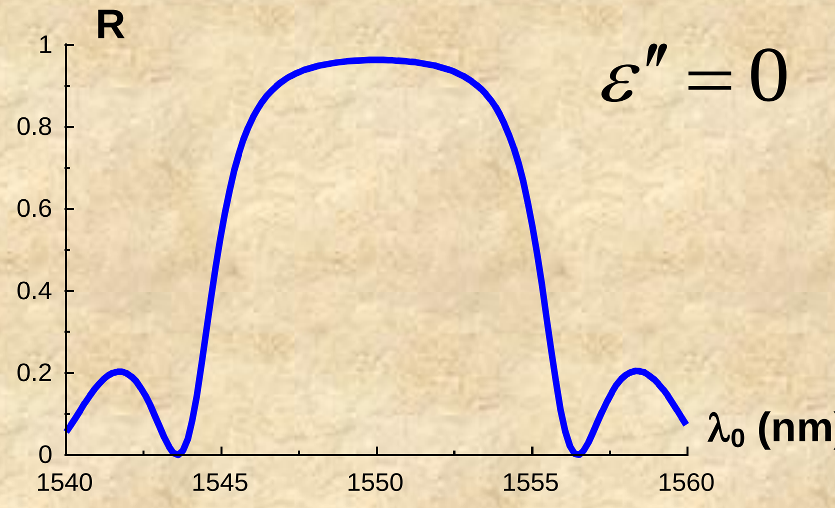
$$\lambda_{0Br} = 1550\,\text{nm} \quad \varepsilon'_0 = 2.25$$

$$L/\Lambda = 300 \quad M = 0.01$$

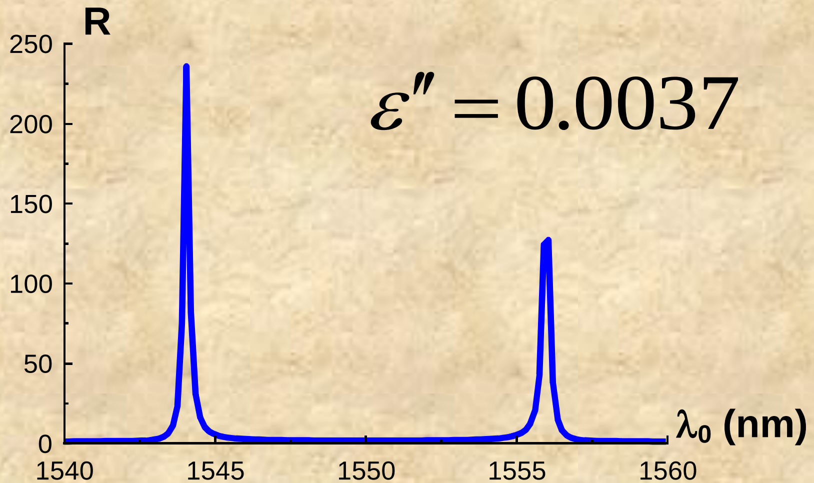
$$\varepsilon'' = 0.0035$$



$$\varepsilon'' = 0$$



$$\varepsilon'' = 0.0037$$



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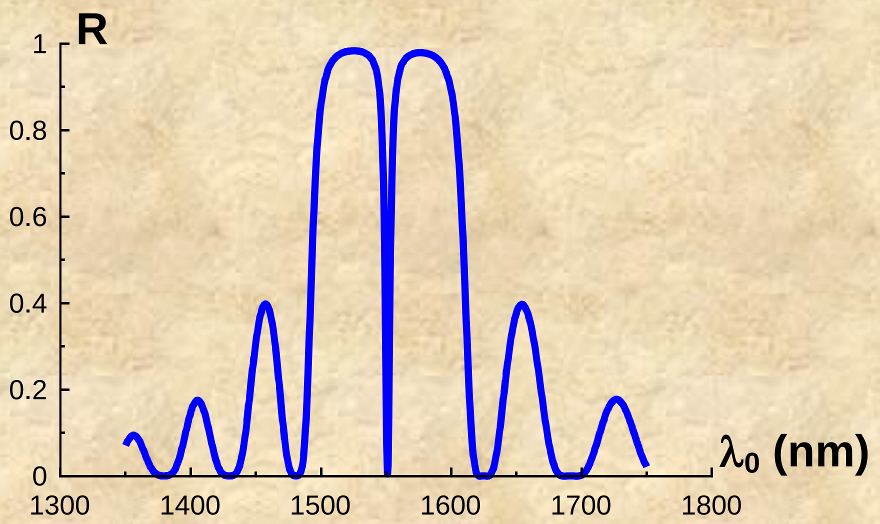
Modelling of DFB fiber laser

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

Reflection spectrum



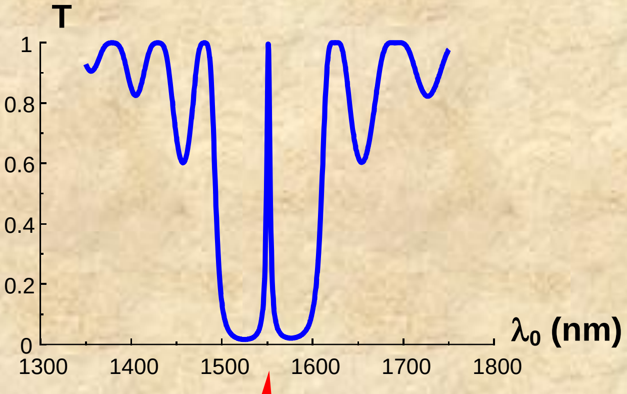
Transmission spectrum

$$\lambda_{0Br} = 1550\,\mathrm{nm} \qquad \varepsilon_0' = 2.25$$

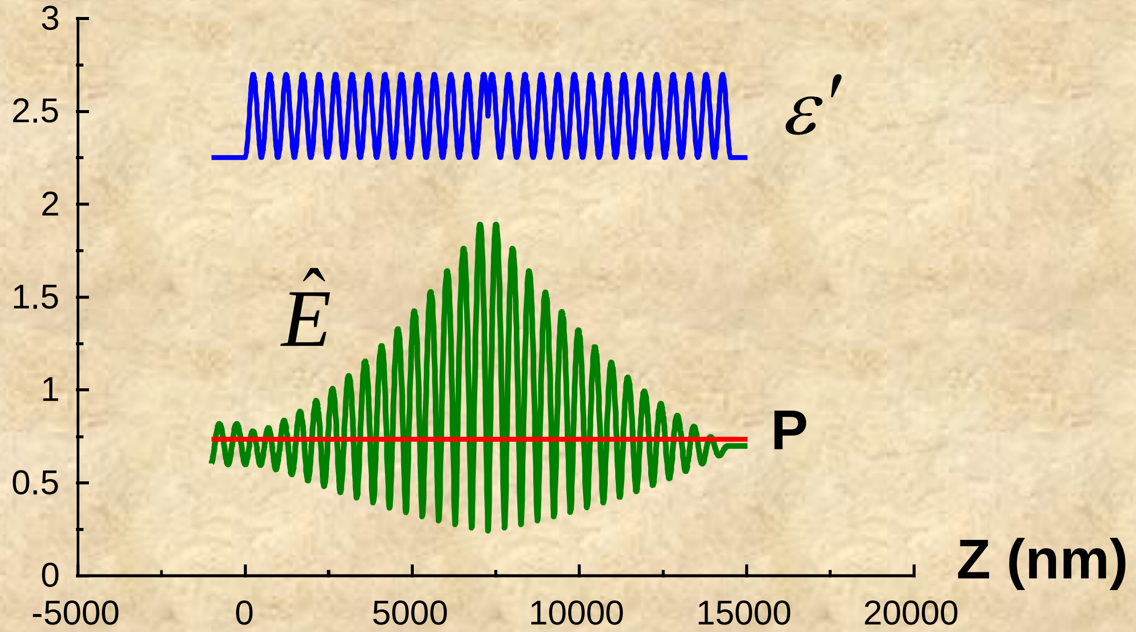
$$L_1 / \Lambda = L_2 / \Lambda = 25 \qquad M = 0.1$$

Modelling of DFB fiber laser

The distributions of the electric field amplitude and the power flow density in a gainless π-phase-shifted FBG $\varepsilon'' = 0$



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



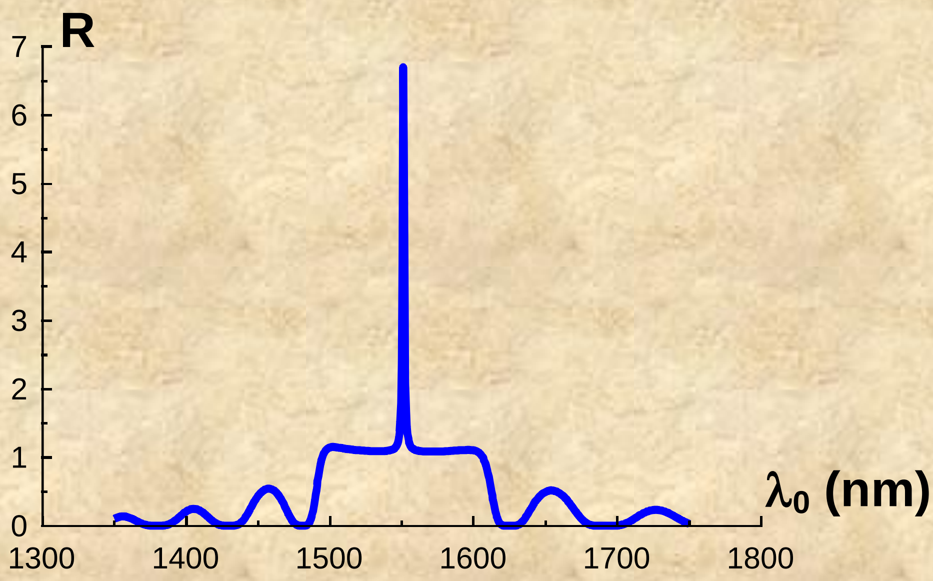
$\varepsilon'_0 = 2.25 \qquad M = 0.1$

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

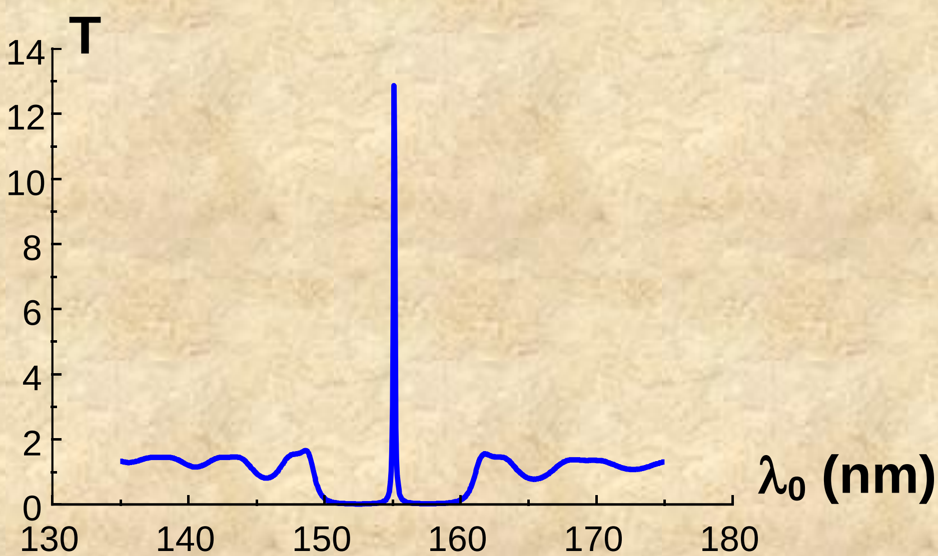
Modelling of DFB fiber laser

Gainy sinusoidal π-phase-shifted FBG $\varepsilon'' = 0.005$

Reflection spectrum



Transmission spectrum



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

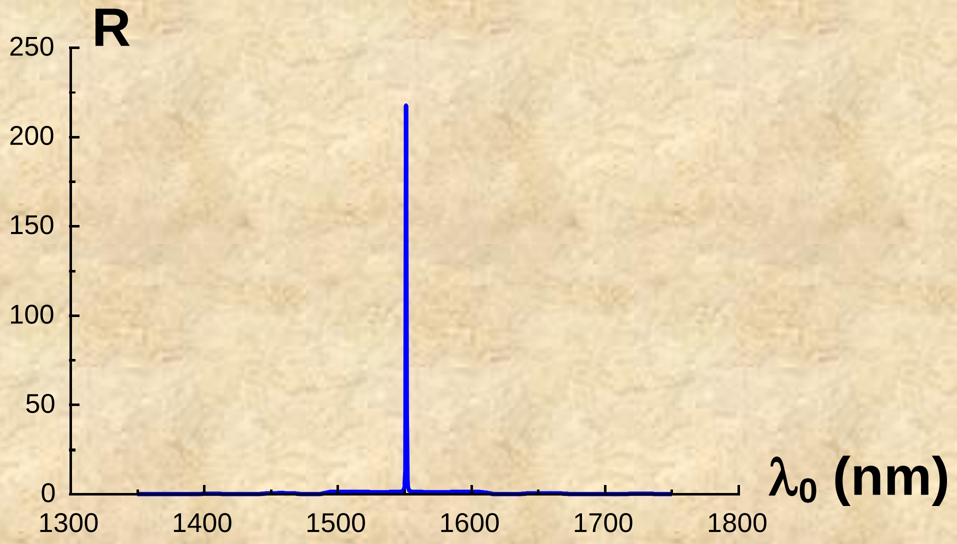
$$\varepsilon_0' = 2.25 \qquad M = 0.1$$

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

Modelling of DFB fiber laser

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

Reflection spectrum



Transmission spectrum

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

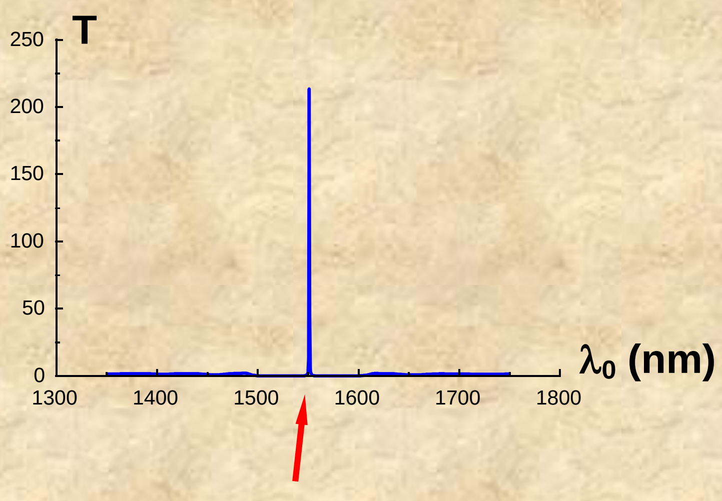
$$\varepsilon_0' = 2.25 \qquad M = 0.1$$

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

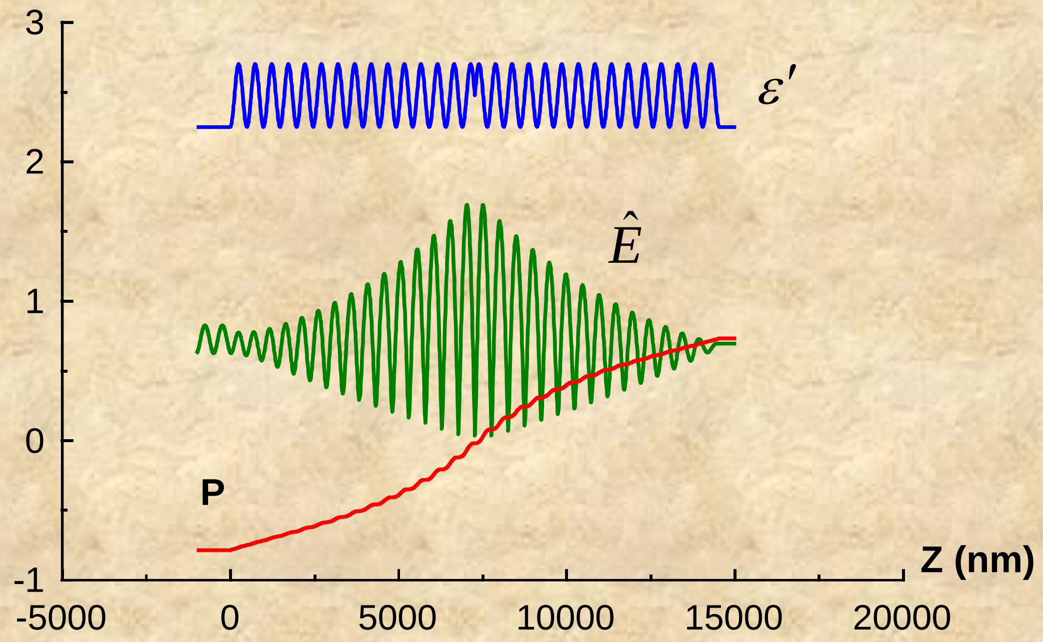
Single-frequency radiation emission at $\lambda_{0Br} = 1550\,\text{nm}$

Modelling of DFB fiber laser

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



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



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

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

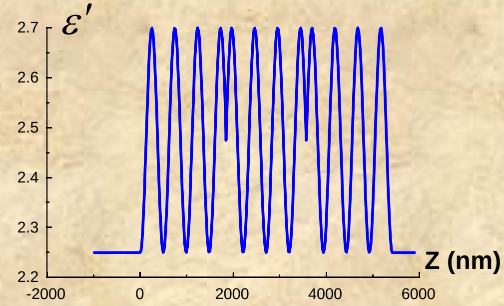
Single-frequency radiation emission at $\lambda_{0Br} = 1550\,\text{nm}$

Modelling of DFB fiber laser

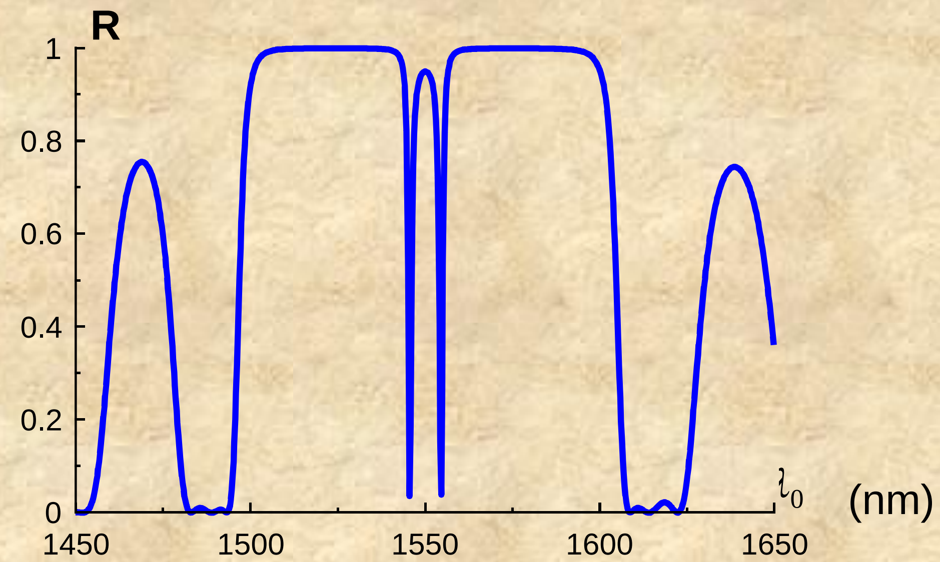
Gainless sinusoidal FBG with equally spaced 2 π-phase-shifts

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

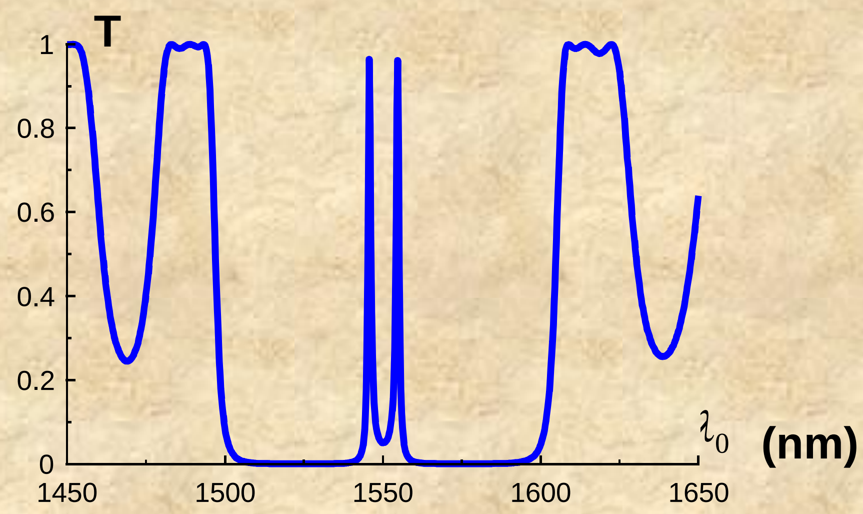
$$\varepsilon'' = 0$$



Reflection spectrum



Transmission spectrum



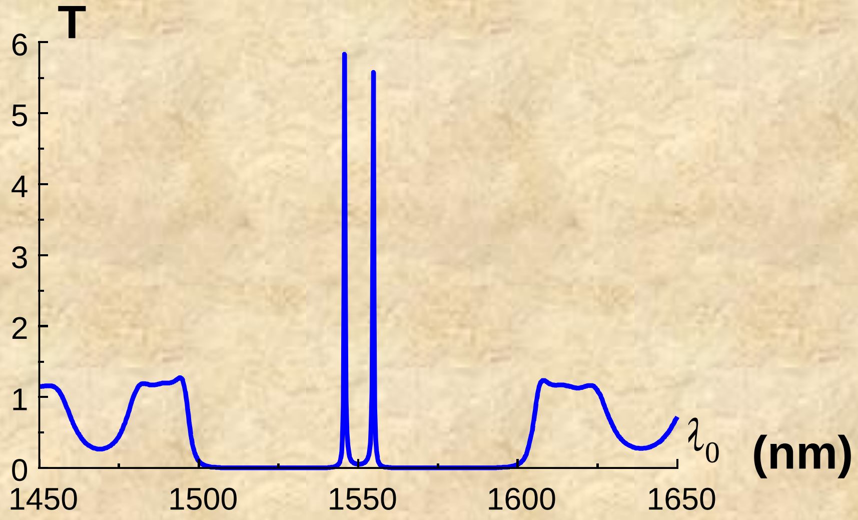
$\lambda_{0Br} = 1550\,\mathrm{nm} \quad \varepsilon_0' = 2.25 \quad M = 0.1$

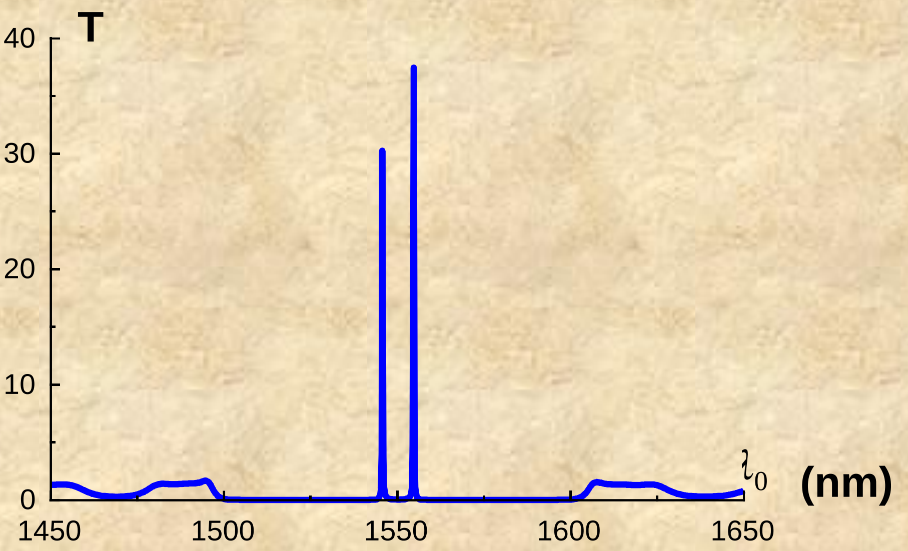
$L_1 / \Lambda = L_2 / \Lambda = L_3 / \Lambda = 30$

Modelling of DFB fiber laser

Gainy sinusoidal FBG with equally spaced 2 π-phase-shifts

Transmission spectra





$$\varepsilon'' = 0.001$$

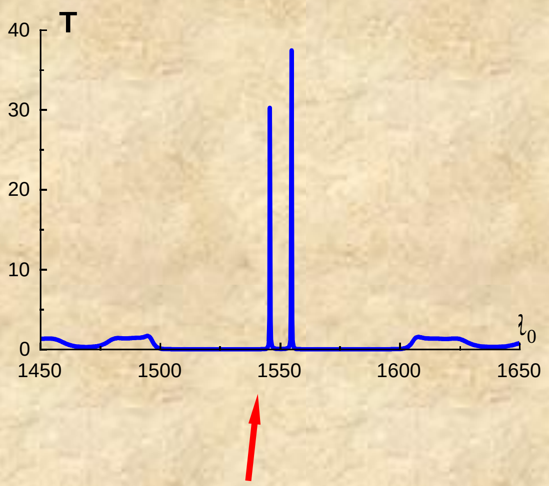
$$\varepsilon'' = 0.002$$

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

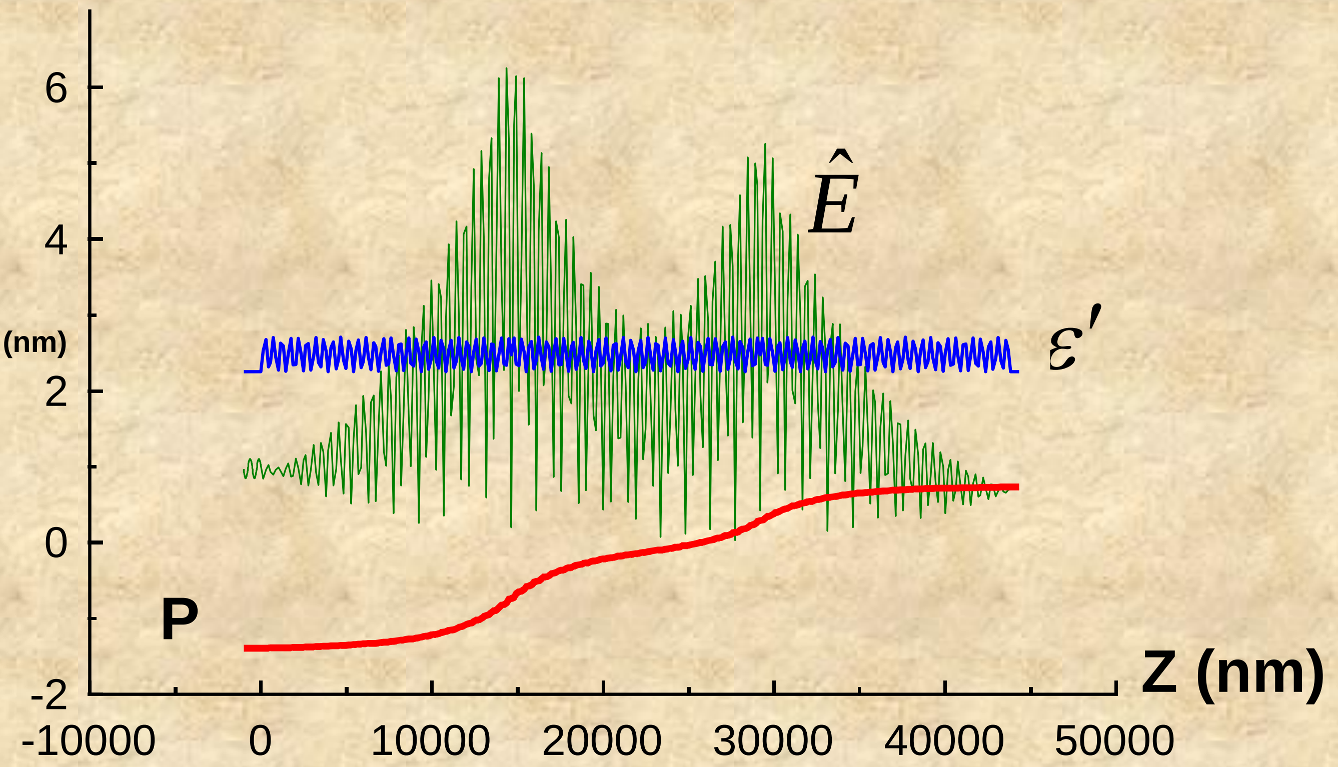
$$L_1 / \Lambda = L_2 / \Lambda = L_3 / \Lambda = 30$$

Modelling of DFB fiber laser

The distributions of the electric field amplitude and the power flow density in a gainy FBG with equally spaced 2 π-phase-shifts



$\lambda_0 = 1545.75\,\text{nm}$



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

$\varepsilon'' = 0.002$

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

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

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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 structure of a uniform FBG without gain leads to an appearance of the two amplified peaks in the reflection spectrum at the edges of the stop-band region of a uniform grating without gain. However at a greater gain a single-mode emission is observed for the left peak .
- 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 advantageous configuration of 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 emission. Power flow density with positive value in the right part of the structure and negative – in the left side of it, also clearly indicates on radiation emission existing from both sides of the single-mode DFB laser.
- Introduction of 2 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.

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Thank you for your attention!