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Optical Narrow Band Filter without Resonances

This paper is dedicated to Professor Karlheinz Tröndle on the ocassion of his 65th birthday

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Abstract: This paper introduces an optical wave filter, which uses gratings at 45° or 135° inclined grating lines that avoid any resonances. Therefore, many more options to form the filter shape exist. In general, the filter design can be traced to that of transversal filters (finite impulse response filter, FIR filter).

Such an integrated optical wave filter is characterized by steep filter slopes and a narrow pass band (less then 0.1nm) combined with a high stop band attenuation (more than 40dB) and a linear phase response in the pass band. Compared to conventional *Bragg* grating filters, the inclined grating line filters can have a flatter pass band and steeper filter skirts related to the width of the pass band. In general, the filter's realization is possible using any optical material. In view of the excellent optical properties the semiconductor material system InP/InGaAsP is used for manufacturing the filter.

Keywords: Integrated optics, optical filters, optical wave filters, inclined grating lines (*Bragg* gratings), III/V-semiconductors, dense wavelength division multiplexing (DWDM), optical waveguide.

1 Introduction

Dense wavelength division multiplexing (DWDM) systems demand of optical signal processing lead to the requirement for filter devices with optimized performance parameters such as narrow bandwidth, flat pass bands, high stop band attenuations, steep filter slopes and small dimensions. Up to now optical wave filters are consisted of waveguides with *Bragg* gratings containing grating lines perpendicular to

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the propagation direction [1]. Multiple resonances between them create the filter function. These filters are recursive filters. The proposed concept uses gratings with inclined grating lines. The filter structure consists of two parallel optical ridge waveguides and a planar waveguide between them. The wave coupled into the first waveguide is reflected by an array of grooves, which are arranged periodically in an angle of 45° to the incoming wave's propagation direction. (For doing so, the first array is called an emitting grating.) The reflected wave is turned through 90°, it is transferred in lateral direction. The second waveguide including a collecting grating receives the wave. The collecting grating contains grooves inclined at 135°. It reflects the wave into its own waveguide. In the second waveguide, the wave propagates in the reverse direction to the propagation direction in the first waveguide. A structure like this is referred to as a Fishbone structure that forms a U-path filter (Fig. 2).

Similar filter structures are known from surface acoustic wave filters (SAW filters) used in the radio frequency range, for example [2], [3]. The filter effect is not due to resonances, as in arrangements of vertical gratings, but it is caused by interferences of wave components propagated on different path lengths. A U-path filter always realizes a bandpass filter function. One advantage of this filter arrangement is that the filter design could attribute to the design of non-recursive filters (finite impulse response filters, FIR filters). With this many more options to form the filter shape exist. Compared to conventional *Bragg* grating filters, the inclined grating line filters can have a flatter pass band and steeper filter skirts related to the width of the pass band. The weighting of the filter coefficients can be converted into the length of the gratings, e.g.. The filter can be realized in a semiconductor material system like InP/InGaAsP.

2 Analysis Model

The structure features two parallel waveguides with gratings, shown in Fig. 2. The grating lines are a distance of Λ apart. Λ is equivalent to the center wavelength of the filter in a given material $\lambda_{M,c} = \lambda_{0,c}/n_{eff}$, where $\lambda_{0,c}$ specifies the center wavelength of the filter under vacuum conditions and n_{eff} the effective refractive index of the material.

The analysis of the groove structure is performed by a two-dimensional model. Each groove structure (grating) contains N grooves (grating lines). A groove structure is seen as being built up of single cells, [4]. It is divided into $M \times (N+M-1)$ cells, $m = 1,2,\ldots,M$ cells in y-direction and $n = 1,2,\ldots,(N+M-1)$ cells in z-direction. There are two kinds of cells, groove cells, which means cells being a part of a groove (grating line), and empty cells.

In Fig. 2 P_i represents the input power and P_o for the output power.

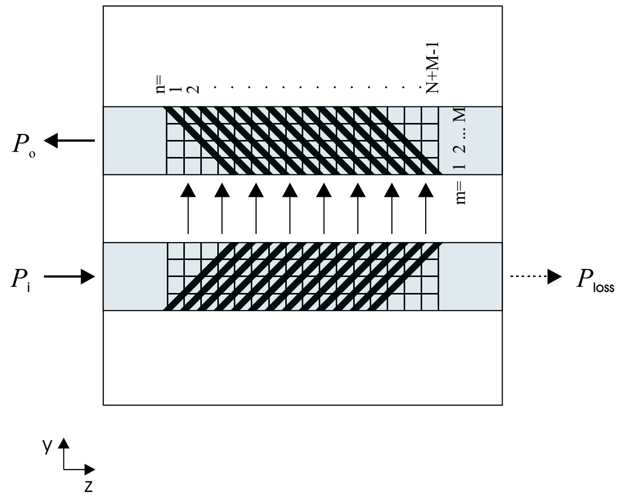

Fig. 1. Schematic structure of the optical wave filter.

Any unit cell has an edge length of $\Lambda \times \Lambda$, with $\Lambda = \lambda_{M,c}$. The cells are 4-ports and can be described by their scattering parameters. For a groove cell of the emitting grating, the reduced 4-port scattering matrix

$$\begin{bmatrix} \underline{u}_{m,n+1} \\ \underline{v}_{m+1,n} \end{bmatrix} = \begin{bmatrix} t_n & \mathrm{i}r_n \\ \mathrm{i}r_n & t_n \end{bmatrix} \mathrm{e}^{-\mathrm{j}2\pi \frac{\Lambda}{\lambda_M}} \cdot \begin{bmatrix} \underline{u}_{m,n} \\ \underline{v}_{m,n} \end{bmatrix} \tag{1.a}$$

is valid. For the collecting grating's cells, the reduced scattering matrix is represented by

$$\begin{bmatrix} \underline{u}_{m,n} \\ \underline{v}_{m+1,n} \end{bmatrix} = \begin{bmatrix} t_n & \mathrm{i}r_n \\ \mathrm{i}r_n & t_n \end{bmatrix} \mathrm{e}^{-\mathrm{j}2\pi \frac{\Lambda}{\lambda_M}} \cdot \begin{bmatrix} \underline{u}_{m,n+1} \\ \underline{v}_{m,n} \end{bmatrix} . \tag{1.b}$$

Herein, $\underline{u}_{m,n}$ stands for the wave parameter in z-direction and $\underline{v}_{m,n}$ is the wave parameter in y-direction. Furthermore, r_n is the magnitude of effective reflection index, t_n the effective transmission index of a groove cell and λ_M the wavelength in the material. It should be emphasized that the reflected wave is phase shifted by 90°. Therefore, $\mathrm{i}r_n$ is the cell reflection coefficient. Λ describes the distance, which the wave part has travelled through the cell. In each cell there are two inclined edges (material transitions) with a distance of $\Lambda/2$ in y- and z-direction, [5]. For modelling the groove cell, the reflection and transmission of the groove section is transferred into the cell center, where r_n is found to be

$$|\underline{r}_n| = \left| 2\sqrt{\Gamma_G} r_s \cdot \sin\left(\underline{k}_1 \frac{1}{4}\Lambda - \underline{k}_2 \frac{1}{2}\Lambda \right) \right| . \tag{2}$$

The reflection of the front groove edge is r_s and Γ_n is the confinement factor of the groove. Furthermore, k_1 is the wave vector of InGaAsP and k_2 that of InP. Finally the transmission is given by

$$t_n^2 = 1 - r_n^2 \,. \tag{3}$$

It should be pointed out that in cells being not a part of any grating line (empty cells), the reflection coefficient is zero and the transmission coefficient becomes one.

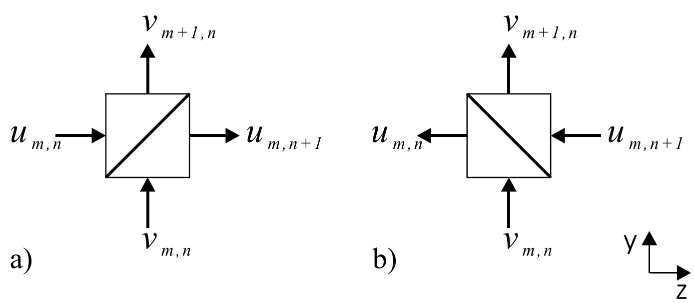

Fig. 2. Description of a groove cell as a 4-port with the scattering parameters, a) groove cell of the emitting grating and b) groove cell of the collecting grating.

3 Implementation of the Filter Function

The two gratings are allocated specific tasks:

The emitting grating has to reflect the incoming wave by 90° and to beam it into the receiving grating. As an additional condition, the outgoing wave magnitude should be constant over the whole grating zone. Therefore, the adjustment of the filter function is realized in the receiving grating.

In an emitting grating with constant reflection coefficients along the wave propagation, the reflected output field decreases nearly exponentially in longitudinal (z-) direction. To compensate this the reflection coefficient has to increase non-linearly along the length of the grating. In conformity with the described emitting grating's tasks, the installation of the constant output wave magnitude is performed under the condition that the observed wavelength is $\lambda_0 \approx \lambda_{0,c}$. Normally cells, which are arranged on the same grating line, have the same reflection coefficient. But for calculation of the emitting structure an approximately calculation is used. Every cells of the grating are filled with grooves. Then the grating structure is divided into columns of cells. The calculation starts from grating line 1 and ends at grating line $(N+M-1)$. Every cells being in the same column has the same reflection coefficient, which is r_n. From a simple input-output calculation this reflection coefficient is determined, $r_n = (\underline{v}_{M+1,n}, \underline{u}_{1,n} \cdots \underline{u}_{M,n}, r_1 \cdots r_{n-1})$, as shown in Fig. 3.

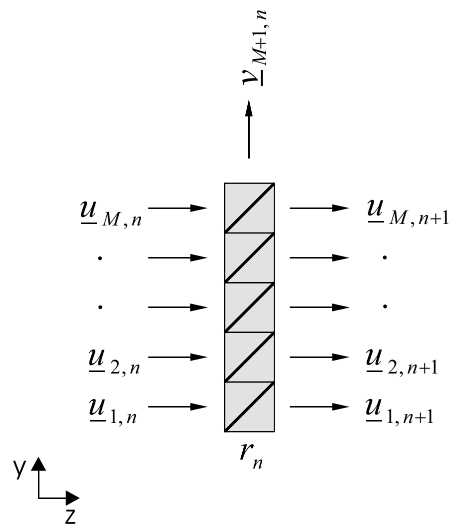

Fig. 3. Schematic structure of the optical wave filter.

Before starting the calculation, a start reflection coefficient r_1 has to be predefined. From it, $\underline{v}_{M+1,1}$ is calculated. For every output n in y-direction $\underline{v}_{M+1,n} = \underline{v}_{M+1,1}$ is valid. Dimensioning the start reflection coefficient r_1 in this way means on the one hand a technological maximum reflection coefficient r_{max} is not transcended and on the other hand a maximum of power is reflected into the receiving grating. After determining, the reflection coefficients are reassigned. They are assigned to the cells, which describes the same grating line. Excessive numbers reflection coefficients are ignored. Except for the first and the last $(M-1)$ the emitting grating's outputs in y-direction, that is a good approach to achieve a constant outgoing wave magnitude.

As stated, the adjustment of the filter function is realized in the receiving grating. The calculation of the collecting array starts with the determination of filter coefficients a_n as such for FIR filters. The aim of the design of transversal filters is to find the best approximation possible for a given filter function. Because the power transfer function is used for viewing the qualities of the optical filter, at first a desired filter function $H^2(\lambda) = P_{out}/P_{in}$ has to be converted into transfer function in the frequency domain, which is $H(f)$. The desired filter function $H(f)$ has to be treated by an inverse discrete Fourier transformation, this way the pulse response $h(t)$ and also the function in the spatial domain $h(z)$ are derived. The elements of the row $h(z)$ are the filter coefficients a_n and the parameter z describes the position of each grating line related to the first grating,

$$z_n = n \cdot \Lambda \,. \tag{4}$$

The difference compared to FIR filter design is that for the inverse discrete Fourier transformation, the double time delay has to be used. This is because the delay of the emitting grating has to be considered.

After the determination of the filter coefficients a_n, in an extended computation each filter coefficient is transformed into a reflection coefficient r_n of the collecting grating. For an exact implementation of a desired filter function each propagation path of the parallel incoming wave component impinging on a specific groove is observed. All the wave components, travelling through two-dimensional model structure with its $M \times (N+M-1)$ cells in the same time, refer to one filter coefficient a_n. Including all possible reflections and transmissions along its propagation path, each component is deemed to be independent from all others. At the output of the collecting grating, all wave components are finally superimposed. This delivers the resultant reflection factor r_n of the relevant grating line.

Finally, any reflection coefficient of both gratings have to be converted into the length of the correlative grating line. Every reflection coefficient refers to a certain confinement factor Γ_n and the latter to a groove length. For calculation of the confinement factors Γ_n from the reflection coefficients r_n equation 1 is used in iteratively. After doing that, the confinement factor is transferred into the length of the groove (grating line). The relation between the confinement factor and the length of the grating line (respectively groove) is dependent on the constructive properties of the filter device.

4 An Example

The transfer function $H(f)$ of an ideal bandpass filter, which means a filter with a rectangular filter characteristic, is transformed into the time domain (respectively spatial domain), leading to a sinc-function. The sinc-function was broken off at $\pm 2\pi$ and weighted with a window function by *Kaiser*, [6]. The *Kaiser* function has 2 parameters, the length α and the form parameter β,

$$w(n) = \begin{cases} \frac{I_0\left(\beta \cdot \sqrt{1-\left(\frac{n}{K}\right)^2}\right)}{I_0(\beta)} & \text{for } -K \leq n \leq K \\ 0 & \text{otherwise .} \end{cases} \tag{5}$$

$I_0(\ldots)$ stands for the modified zeroth order Bessel function of the first kind. N, the number of grooves, equals the length of the window and $\alpha = (N-1)/2$. As an compromise between mainlobe width and sidelobe amplitude in the filters presented here, the form parameter β was chosen to be 3.4. One particular filter shall be looked at in more detail. It consists of 5531 grooves and has a width of 8 cells.

Beside a linear phase response in the pass-band the filter shows following parameters:

Table 1. Parameters of the viewed filter.

number of grooves (grating lines)	stop band attenuation	3 dB band-width
5531	> 40 dB	0.48 nm

The filter transfer function of the U-path-filter has a 3dB-bandwidth, which is half as large as that in the underlying FIR filter (Fig. 4).

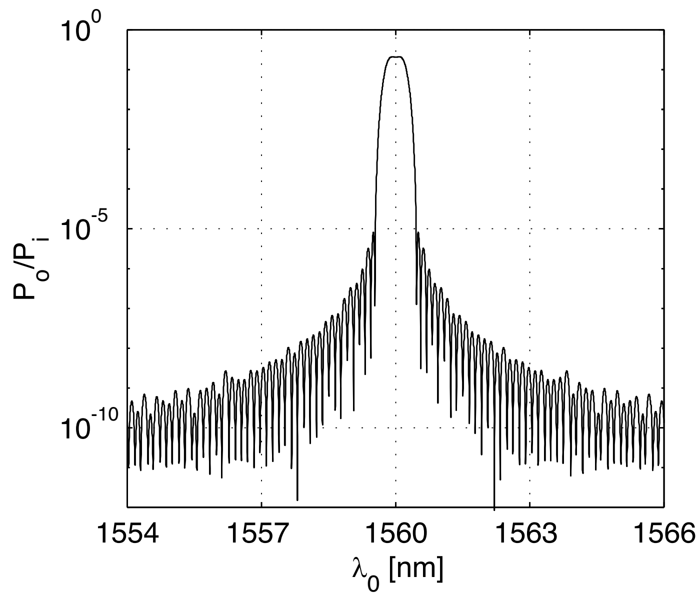

Fig. 4. Transfer function $\left|H^2(\lambda_0)\right| = Po/Pi$ of U-path-filters with 5531 grooves and a width of 8 cells.

5 Device Realization

For the practical realization of the optical wave filter, the semiconductor material InP/InGaAsP is used. The construction of the optical wave filter is displayed in Fig. 5.

The design has been carried out for the use at a wavelength of 1.56μm. Nevertheless, dimensioning for arbitrary wavelengths is possible, for example 1.30μm.

The waveguides are realized by buried ridges of InGaAsP carrying the inclined grooves of InP. Between the ridge waveguides, the reflected optical field is guided

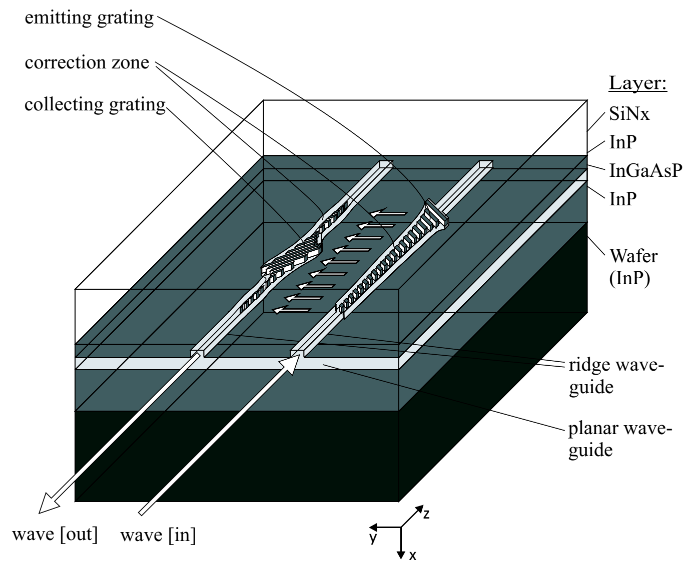

Fig. 5. Overview of the filter.

by a planar waveguide of the InGaAsP-Layer. Waveguiding is caused by the differences of the refractive index between InP and InGaAsP, in z-direction ridge waveguides of InGaAsP and in y-direction by a planar waveguide. Similar waveguide structures using the material system Si/SiGe has been described in [7].

In the waveguides of InGaAsP, grooves of InP inclined at 45° or 135° are installed. The waveguides widen up in this area. Any change of k_{eff} destroys the periodicity of the wave along the gratings and causes a phase mismatching of the grooves. But the effective refractive index n_{eff} and so the wave number k_{eff} has to be held constant over the complete length (lateral extension) of the waveguide. Therefore, the width of the waveguides is not changed proportional to the width of the grooves or the weighting of the grooves. The gimmick is to bring in a correction zone. This correction zone allows the effective refractive index to remain constant over the whole lateral extension of ridge waveguide.

6 Conclusions

A novel integrated optical wave filter was presented. It consists of two coupled waveguides with 45° or 135° inclined grooves. The presented filter is designed at the wavelength of 1.56μm. It is characterized by a bandwidth of 0.48nm and a close stop band attenuation of more than 40dB combined with steep filter slopes. But bandwidths less then 0.1nm are possible. In principle, the filter design refers to the FIR filter design. So the filter has all the advantages that a FIR filter had previously. For the first realization, we chose the material system InP/InGaAsP. The structure of the optical wave filter can be extended to insert a pin-diode with the InGaAsP-layer as an intrinsic zone. In this way an amplification can realized by using the effect of stimulated emission.

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