Volume diffraction gratings for optical telecommunications applications: design study for a spectral equalizer

T Loukina, S Massenot, R Chevallier, Kevin Heggarty, N Shigapova, A Skochilov

To cite this version:

T Loukina, S Massenot, R Chevallier, Kevin Heggarty, N Shigapova, et al.. Volume diffraction gratings for optical telecommunications applications: design study for a spectral equalizer. Optical Engineering, SPIE, 2004, 10.1117/1.1803848] . hal-01828789

HAL Id: hal-01828789
https://hal-imt-atlantique.archives-ouvertes.fr/hal-01828789
Submitted on 3 Jul 2018

Volume diffraction gratings for optical telecommunications applications: design study for a spectral equalizer

T. Loukina
GET/ENST Bretagne
Technopole Brest Iroise
CS 83818
29238 Brest Cedex 3, France
and
State Institute of Applied Optics (GIPO)
420075, Kazan, Russia
E-mail: tatiana.loukina@enst-bretagne.fr

S. Massenot
R. Chevallier
K. Heggarty
GET/ENST Bretagne
Technopole Brest Iroise
CS 83818
29238 Brest Cedex 3, France

N. M. Shigapova
A. F. Skochilov
State Institute of Applied Optics (GIPO)
420075, Kazan., Russia

[DOI: 10.1117/1.1803848]

Subject terms: spectral equalization; surface relief gratings; volume-phase holographic gratings; dichromated gelatin; packaging; optical telecommunications.

Paper 431108 received Dec. 1, 2003; revised manuscript received Jun. 30, 2004; accepted for publication Jul. 27, 2004.

The main characteristics required for a diffraction grating used for (de)multiplexing functions in spectral equalizing systems are investigated, both theoretically and experimentally. We show that volume-phase holographic (VPH) gratings can be used as dispersive elements instead of classic reflection surface-relief gratings presently employed in most optical telecommunications devices. A design method for this type of diffraction grating and experimental results are presented, confirming that VPH gratings are well suited to such applications.

1 Introduction

Optical telecommunications networks have improved considerably over the last ten years, in order to constantly satisfy the growth of bit rate, mainly due to the internet traffic increase and the multiplication of multimedia services.

The main technological advances that have permitted this evolution are the introduction of the optical amplifier at the end of the 1980s and the use of wavelength division multiplexing (WDM) in the middle of the 1990s. These advances have led to a need for specific components and subsystems, particularly spectrally selective components to assure filtering functions or those with a high dispersive power for wavelength multiplexing functions.

In WDM systems, several wavelengths (often referred to as channels, each corresponding to an optical carrier) propagate simultaneously. These optical carriers are defined by the so-called ITU grid. The spectral bandwidth currently used in optical links is the C band (C for conventional) and is defined for channels going from $\lambda = 1530.33$ nm to $\lambda = 1569.59$ nm with a spacing of around 0.8 nm (which corresponds to a frequency spacing of 100 GHz; the ITU grid is defined in frequency).

When designing a diffraction grating for use in a telecommunications system, the technical constraints are strongly linked to the application domain. Diffraction gratings can be used for example as filters, demultiplexers, or dispersive elements in spectral equalizers. The constraints will not be the same for these three applications, in particular spectral selectivity and dispersive power will not be optimized in the same way.

The aim of this paper is to present a design method for a diffraction grating destined for optical telecommunications. A universally applicable component does not exist, so the method presented here will be tailored for a specific application. We will illustrate this with a concrete example: the design of a dispersive element used in a spectral equalizer.

First we review the main characteristics of diffraction gratings (either surface-relief or volume-phase holographic gratings). Then we present the telecommunications application and the constraints the diffraction grating has to satisfy in order to guarantee optimal performance of the final component.

We will show the link between the gratings' properties and the constraints imposed by the desired application in order to extract the engineering rules and trade-offs involved in the design of such gratings.

Finally, experimental results will be presented where we show that the present approach is validated since it fullfils all specifications required by this specific telecommunications application.

2 General Characteristics Required for a Diffraction Grating Used in Telecommunications Systems

2.1 *Main Diffraction Grating Characteristics*

We recall here the main physical characteristics of diffraction gratings, which are pertinent for our application.

Diffraction efficiency. The diffraction efficiency (DE) in a given diffracted order m is defined by the ratio between the diffracted intensity in this order and the incident beam intensity: $DE_m = I_{difm}/I_{inc}$. It is wavelength, angle, and polarization dependent.

Polarization sensitivity. For gratings with high spatial frequencies (grating period Λ is the same order as the operating wavelength λ), the diffraction efficiency can be different for two orthogonal polarizations (TE when the electric field is parallel to the grooves of the grating and TM when it is perpendicular to the grooves). The grating is defined to be polarization insensitive if the difference between corresponding diffraction efficiencies is less than a few percent.

Spectral uniformity. We mentioned above that the diffraction efficiency is wavelength dependent. The need for a spectral uniformity of diffraction efficiency depends strongly on the application. For example, for spectral equalizing it is desirable to have a spectral response as flat as possible (this is not the case if we are interested in filtering functions).

Angular dispersion. The classical grating equation is given by:

$$m\lambda = \Lambda(\sin\alpha + \sin\beta_m) \tag{1}$$

where α is the angle of incidence, β_m is the angle of the m'th diffracted order (the angles are measured from the grating normal), and Λ is the period of the grating ($\Lambda = 1/\nu$, where ν is the spatial frequency given in mm^{-1}).

The angular dispersion of the grating is the angular separation between different wavelengths in the same diffracted order:

$$D = \frac{\partial\beta_m}{\partial\lambda} = \frac{m}{\Lambda\cos\beta_m} \tag{2}$$

The angular dispersion for a given spatial frequency can be improved by increasing the angle β_m (grazing incidence) or by using asymmetric fringes for a volume-phase holographic grating. For an optical system, we are more interested in the spatial dispersion, which is the product of the angular dispersion D [see Eq. (2)] and the focal length of the system f.

2.2 *Telecommunications Viewpoint*

2.2.1 *Focused application: a spectral equalizer*

In optical telecommunications, a spectral equalizer is a component able to modify the spectrum of a signal by introducing selective losses using a reconfigurable element over a wavelength range. This equalizer is said to be dynamic if it is reconfigurable. The main functions that this component can provide to optical networks are gain equalization (the wavelength dependence of an optical amplifier gain has to be corrected in order to have the same signal quality over the C band) and wavelength routing (mainly destined to the next generation of optical networks). A basic schematic of a spectral equalizer is shown in Fig. 1.

Concerning the diffraction grating, the retained architecture for the spectral equalizer imposes some requirements on this diffraction grating. In this configuration, the grating has to work at a fixed incidence, in a non-Littrow mount and has to work in a double-pass scheme (hence the need for a high diffraction efficiency).

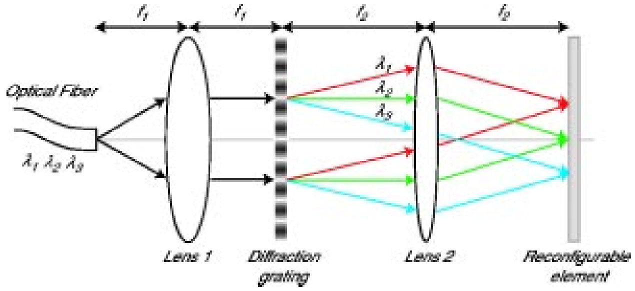

Fig. 1 Example of a spectral equalizer architecture.

2.2.2 *Critical parameters for diffraction gratings used as dispersive elements in a telecommunications system*

When a new component is introduced in an optical link, it generally degrades the signal quality. This leads to system penalties, principally the following.

Insertion loss (IL). This corresponds to the optical power loss generated by the component. It is defined as the ratio between the output and input powers. In telecommunications, the typical unit is the decibel (dB), so the insertion loss in dB corresponds to the difference of the output and input powers in dBm (logarithmic optical power relative to 1 mW).

$$\mathrm{IL(dB)} = P_{out}(\mathrm{dBm}) - P_{inc}(\mathrm{dBm}) \tag{3}$$

Polarization dependent loss (PDL). Another characteristic is the loss due to the components' polarization sensitivity. Since, the polarization state of a beam at the output of a fiber is generally unknown, the response of a component used in telecommunications has to be the same (with as little variation possible) whatever the polarization state. The quantity that measures this polarization sensitivity is called polarization dependent loss (PDL). It is defined as the ratio between the maximum and minimum powers at the output for all possible input polarization states. In telecommunications, it is defined in dB by the difference of these two optical powers (maximum and minimum) in dBm. For a diffraction grating, it is given by the logarithm of the ratio between diffraction efficiencies DE for the TE and TM polarization states:

$$\mathrm{PDL} = 10\left|\log\left(\frac{DE_{TE}}{DE_{TM}}\right)\right| \tag{4}$$

Wavelength dependent loss (WDL). This penalty is linked to the wavelength dependence of the insertion loss (IL), and it defines the uniformity of IL on the considered spectral bandwidth. It is defined as the difference in dB between the maximum and minimum values of loss due to the variation of the wavelength and given by:

Table 1 Main physical characteristics and requirements of a diffraction grating and the corresponding telecommunications system parameters.

Grating characteristic	System parameter
Diffraction efficiency (DE)	Insertion Loss IL=10 log DE
Spectral uniformity	Wavelength Dependent Loss (WDL)
Polarization sensitivity	Polarization Dependent Loss (PDL)
Angular Dispersion (D)	System resolution

$$\mathrm{WDL(dB)} = \mathrm{IL}_{\max}(\mathrm{dBm}) - \mathrm{IL}_{\min}(\mathrm{dBm}) \tag{5}$$

where $\mathrm{IL}_{\max}$ and $\mathrm{IL}_{\min}$ are the maximum and minimum insertion loss of the grating over the whole spectral bandwidth.

Another important parameter is the system resolution. It is not considered as a penalty but it is linked directly to the focused application and the design of the component depends on this parameter. For a system using a dispersive element the resolution is linked to the angular dispersion. For a classical multiplexing function, all channels have to be separated by the diameter of an optical fiber (125 μm).[1,2] Also, to reduce overall system size, the grating should be highly dispersive. For spectral equalizing systems, the constraints are not the same, in particular the required resolution is lower than for multiplexers/demultiplexers. The behavior of the grating will be different and specific engineering rules in the design have to be used. Hence, the value of spatial dispersion defines a couple (focal length f/spatial frequency ν) for which we can satisfy the specifications of the system.

2.3 *Equivalences between Grating Characteristics and Telecommunications Parameters*

The equivalences between grating characteristics and telecommunications systems parameters are defined in Table 1.

For a grating used as dispersive element in a spectral equalizer, typical specifications are:

IL<1.0 dB (diffraction efficiency more than 80%)

PDL<0.1 dB (diffraction efficiency variations with polarization state less than 2%)

WDL<0.1 dB (diffraction efficiency variations with wavelength less than 2%)

The system resolution depends strongly on the application and the packaging constraints (nearly 0.02 deg/nm in our case).

2.4 *Industrial Constraints*

This section addresses mass-production and packaging constraints. Like all optical components used in telecommunications systems, diffraction gratings must be inexpensive in mass production. A good reproducibility and stability of technological process are required to maintain systems specifications. The diffraction grating should also be easy to manipulate and present a highly protected surface.

Telecommunications equipment must withstand rigorous environmental constraints. They can be used either in subsea links or in terrestrial networks in different climates. Diffraction gratings used in such equipment contribute to the reliability of the component. These constraints are specified by standardization organisms. For example, Telcordia's assessments indicate that the IL and PDL variations must be less than 0.1 dB when the grating is submitted to severe thermal constraints. Devices must also pass the high-temperature storage test (+85°C), low-temperature storage test (−40°C), and thermal operating cycles from −5°C to +70°C. The number of hours and cycles is specified by standards (full details are given in the Telcordia specification GR-1221-CORE concerning passive optical components).

Although the angular selectivity is a physical characteristic, we treat it in this section because it is directly related to the mechanical precision of the system. If we have a flat diffraction efficiency versus the incidence angle over the desired spectral bandwidth, angular tolerances of mechanical alignment can be relaxed. This can lead to cost reductions for the manufacturer.

3 Choice of Grating

3.1 *Which Types of Grating Can Be Used?*

Among the diverse family of diffraction gratings, we have to choose those which satisfy the required physical parameters (high diffraction efficiency, high spectral uniformity over the C band, low PDL, low angular selectivity, etc).

If we retain the diffraction efficiency value as a criteria, we have to orient our choice to phase gratings, which are more efficient than amplitude gratings. Then, we have to choose between thick transmission volume-phase gratings and reflection surface relief gratings. Thick reflection volume-phase gratings are more suitable for filtering functions.

3.2 *Surface Relief Grating*

Reflective surface relief gratings in the Littrow configuration are probably the most used diffractive elements in spectrometry and telecommunications. They have already proved their efficiency for standard multiplexing operations.[2] With a suitable blaze angle, a high reflective diffraction efficiency in a fixed order can be obtained.

Another parameter to take into account is the presence of Wood anomalies for TE polarization, which produce undesirable brutal changes in the diffraction efficiency response of the grating. These are often present for this type of grating. That is why it is impossible to provide polarization independence for arbitrary spatial frequencies.

One solution is to use this grating with optimal polarization. For such a solution, we have to split the input signal into its two principal states and use a polarization diversity system. The two beams (having the same polarization state) are then recombined after passing through the grating. A disadvantage of this solution is that it can introduce an optical path difference between the two principal states of polarization, which leads to a pulse spreading. This phenomena is called polarization mode dispersion in telecommunications[3] and leads to a degradation of the signal quality. Another major disadvantage is the increase in the number of components and hence the cost.

An alternative solution is to manufacture gratings with nonstandard profiles in order to obtain the same efficiency for both polarizations. Among these solutions, we can cite:

the corners of the grating profile are rounded[4]

the superposition of different etch depths[5] or grating periods[6,7]

a wise choice of the incident medium[8] provides good results for some restricted applications.

A major disadvantage lies in the fact that such profiles are difficult to manufacture. In addition, the optimization for polarization independence is available only for certain values of grating periods or wavelengths, which restricts the field of applications.

A major advantage of a classical surface relief grating is the ability to produce many replicas with a single master grating, greatly reducing the costs. On the other hand, surface relief gratings are considered to be fragile. Performance degradations occur if the surface is contaminated during assembly or during operation.

3.3 *Volume-Phase Holographic Gratings*

3.3.1 *Introduction*

Volume-phase holographic gratings are starting to find industrial applications, for example in astronomy and spectroscopy[9–11] and wavelength division multiplexing.[12–14]

It is theoretically possible to obtain a 100% diffraction efficiency in the first order for a thick volume-phase grating working under Bragg conditions. A hologram can be considered as "thick" if the Klein factor Q, which is determined by

$$Q=\frac{2\pi\lambda T}{\overline{n}\Lambda^2\cos\theta}, \tag{6}$$

is higher than 10. Here T is the thickness of the grating, $\overline{n}$ is the average refractive index, θ is the incident angle inside the grating, and Λ is the grating period.

In this case, the classical theory of Kogelnik[15] gives excellent results. Very good agreement was obtained by comparing this theory with results given by the rigorous coupled-wave theory of Moharam and Gaylord[16] (a stable implementation was used[17] in order to avoid numerical contaminations due to the high thickness of the volume phase grating).

Under Bragg conditions, the maximum of diffraction efficiency for transmission gratings is defined by:

$$DE=\sin^2 v \tag{7}$$

where v depends on the polarization of the incident beam:

$$\begin{cases} v_{TE}=\dfrac{\pi\Delta n T}{\lambda\cos\theta} \\ v_{TM}=v_{TE}\cos(2\theta) \end{cases}. \tag{8}$$

Here θ is the Bragg angle inside the grating.

In addition, this theory enables us to express the spectral bandwidth for transmission VPH gratings by[15]:

$$\Delta\lambda\simeq\frac{\Lambda}{T}\lambda\cot\theta. \tag{9}$$

The polarization sensitivity is proportional to the $\cos(2\theta_B)$ [see Eq. (8)] term, which means that if we have a maximum for the TE polarization, the maximum for the TM polarization will be shifted to shorter wavelengths (both polarizations can reach 100% diffraction efficiency). In the following, we will see that the polarization sensitivity can be reduced by adjusting parameters such as grating thickness T and refractive index modulation Δn.

The principal benefits of VPH gratings in comparison with surface relief (SR) gratings are the following:

theoretical diffraction efficiency up to 100%

VPH gratings lack many of the grating anomalies apparent in SR gratings

VPH gratings can be produced with arbitrary spatial frequencies

low polarization sensitivities are possible with low and high dispersion transmission VPH gratings

VPH gratings can be tuned to shift the diffraction efficiency peak to a desired wavelength.

Both gratings (VPH and SR) can have their surfaces protected from impurities but VPH gratings are encapsulated between two glass substrates, hence their optical surfaces are naturally protected. Antireflection coatings can be applied to the outer surfaces to minimize Fresnel reflections and maximize throughput.

VPH gratings have disadvantages concerning the reproducibility of the process; all the recording parameters must be controlled precisely (humidity if we use dichromated gelatin, for example). In addition, there are few manufacturers of suitable photosensisitive materials.

We can see that both surface relief and volume-phase holographic gratings are suitable for multiplexing functions. The choice between these two gratings is not clear: both have advantages and disadvantages. Generally, surface relief gratings are used for such applications, and they have been widely studied.[1,2] We will show in the following that a volume-phase grating can also satisfy telecommunications requirements.

3.3.2 *Design rules*

The design of a VPH grating destined for telecommunications has to satisfy the following trade-offs in order to satisfy the physical and industrial constraints:

Diffraction efficiency/WDL. The spectral uniformity over a working spectral band for a given spatial frequency and for transmission VPH gratings can be improved to the detriment of the maximum diffraction efficiency (see, for example, Ref. 14).

WDL/hologram thickness. Equation (9) shows that the spectral bandwidth (and consequently the spectral flatness) and the hologram thickness are inversely proportional.

Hologram thickness/refractive index modulation. For fixed wavelength and spatial frequency, these two parameters determine the maximum achievable diffraction efficiency [DE=100% if $v_{\mathrm{TE}}=\pi/2$ into Eq. (8)].

Angular dispersion/polarization sensitivity or PDL. Both parameters depend on Bragg angle. The grating's PDL is minimal if $\cos(2\theta)\sim 1$.

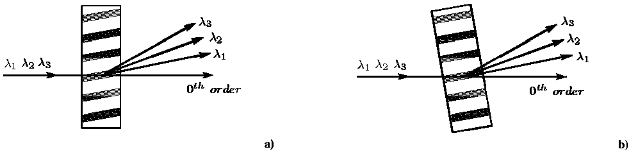

Fig. 2 Grating configuration: (a) asymmetric and (b) symmetric.

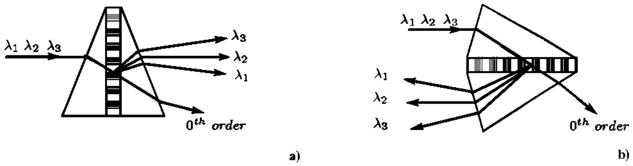

Fig. 4 Grism configuration: (a) inline or (b) with angular deviation.

Angular selectivity/mechanical precision. The holographic material must be chosen to satisfy the volume condition and to provide a sufficiently high refractive index modulation. The designer must allow for diverse changes in the material caused by the process (recording and development)[18] (this aspect is described in more detail in Sec. 4.2).

4 Volume Phase Holographic Grating Used for Spectral Equalization Systems

As explained above, we selected the transmission volume-phase holographic grating for our application, and we now present simulation results that show the behavior of such a grating. We will be able to check that such gratings satisfy the requirements described in Sec. 2.

For a spectral equalizer application, taking into account the architecture, the tunability required, and that the typical WDM channel spacing is 0.8 nm, the required spatial dispersion (product fD) is of the order of 0.02 mm/nm.

4.1 *Spatial Frequency Design*

For different focal lengths f of the system and for a given spatial dispersion, we will derive first the appropriate grating spatial frequency. Then using Kogelnik's theory as a modeling tool, we will determine which of these gratings is the most likely to give the best physical parameters.

The determination of the spatial frequency ν is achieved by solving the system:

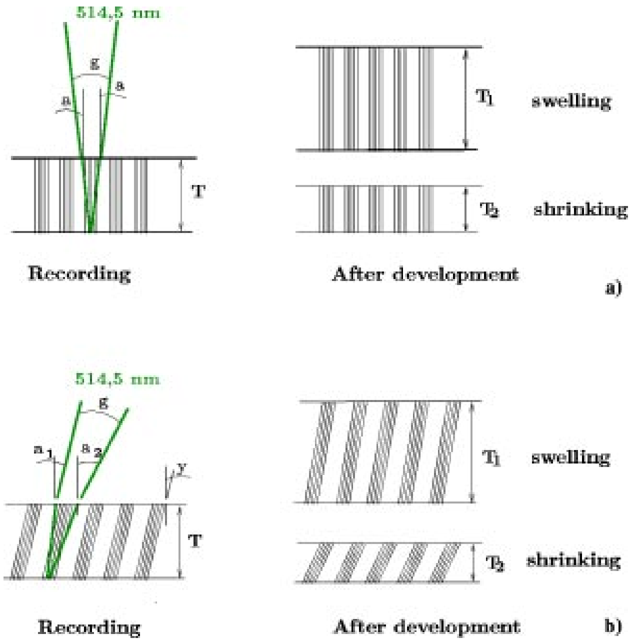

Fig. 3 Illustration of swelling and shrinkage effects into holographic materials for (a) symmetric and (b) asymmetric gratings.

$$\begin{cases} Df = \dfrac{\nu f}{\cos\beta} \\ \sin\beta = \nu\left(\dfrac{\lambda_0 \pm 2\Delta\lambda}{2}\right) \end{cases} \tag{10}$$

where $\lambda_0 = 1550\,\text{nm}$ is the central wavelength for the C band and $\Delta\lambda = 20$ nm is the half spectral bandwidth.

The focal length of the system depends strongly on the architecture and packaging constraints. We will give simulation results with focal lengths suitable for our spectral equalization application. As an example, we take values of 100 mm, 75 mm, 50 mm, and 25 mm. The corresponding spatial frequencies are: $\nu_1 = 230\,\text{mm}^{-1}$, $\nu_2 = 300\,\text{mm}^{-1}$, $\nu_3 = 440\,\text{mm}^{-1}$, and $\nu_4 = 750\,\text{mm}^{-1}$.

4.2 *Symmetric or Asymmetric Grating*

The easiest way to use a grating and a component in general is at normal incidence, which makes the packaging easier. As shown in Fig. 2(a), a grating with tilted (asymmetric) fringes is able to work at normal incidence unlike an untilted (symmetric) transmission grating Fig. 2(b).

However, using a tilted holographic grating presents some disadvantages from a technical viewpoint. Volume-phase gratings are recorded optically in an appropriate holographic material such as dichromated gelatin (DCG) or photopolymers. Both of these materials are capable of providing sufficient refractive index modulation to give high diffraction efficiencies. But these materials have defects due to the recording and development processes. DCG and photopolymers undergo respectively a swelling and a shrinkage, which change the angle of the fringes (and con-

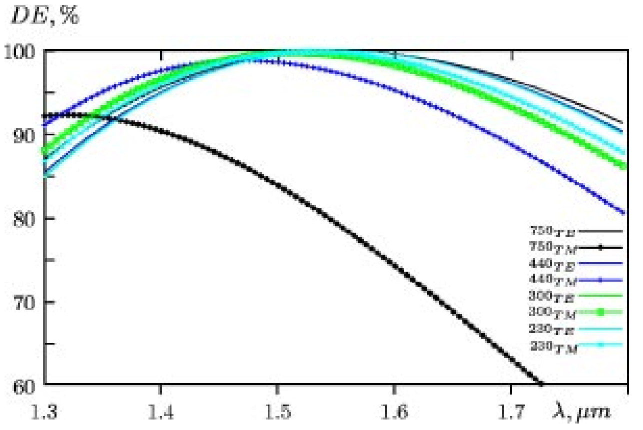

Fig. 5 Diffraction efficiency versus wavelength for four different gratings. The grating thickness for each grating spatial frequency is different to satisfy the volume grating condition $Q = 10$: 2.5 μm for 750 mm^{-1}; 7.7 μm for 440 mm^{-1}; 21.7 μm for 300 mm^{-1}; and 28.0 μm for 230 mm^{-1}.

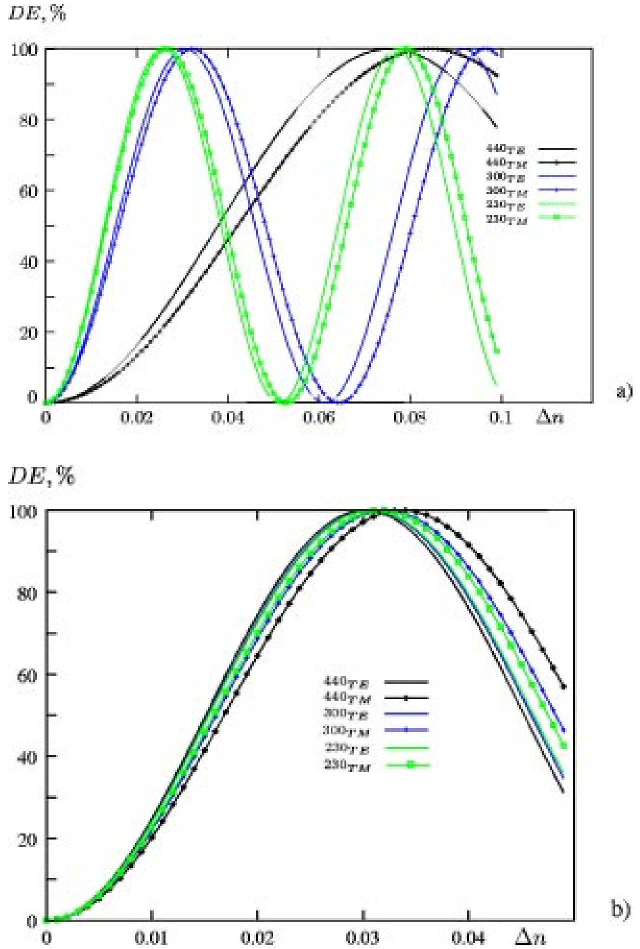

Fig. 6 Diffraction efficiency as a function of index modulation: (a) grating thickness varies with spatial frequency: 10 μm for 440 mm^{-1}, 25 μm for 300 mm^{-1}, and 30 μm for 230 mm^{-1}; (b) grating thickness is constant (25 μm).

sequently the period) of the grating if it is asymmetric (see Fig. 3). As a result, the diffraction efficiency maximum will not be centered on the spectral bandwidth for normal incidence. These effects are not easy to control in an industrialization situation, hence our choice of a symmetric grating, whose period is not affected by the development process and for which Bragg angle is constant.

It is possible to work inline with an untilted transmission grating by using a grism configuration[19,20] (see Fig. 4). The angles of the prisms are calculated in order to be at Bragg incidence for the center wavelength of the spectral bandwidth. Prism dispersion (traditionally made of standard glasses like BK-7) can be neglected inside the relatively narrow operating spectral bandwidth (only 40 nm).

4.3 *Simulation Results*

To maximize the diffraction efficiency of a VPH grating, we have to optimize two parameters, which are the thickness T of the holographic material and the refractive index modulation Δn [according to Eq. (8)]. These values have to be realistic compared to values obtainable with holographic materials. On the other hand, for a given spatial frequency, low values of grating thickness [according to Eq. (10)] allow optimization of spectral flatness and WDL.

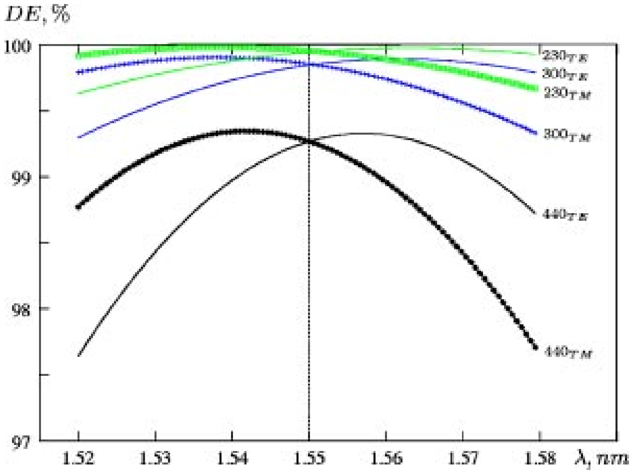

Fig. 7 Improved spectral diffraction efficiency for three VPH gratings with the same grating thickness (25 μm) and a refractive index modulation of nearly 0.03 for each grating.

In Fig. 5, we present spectral curves for four different gratings; the thickness for each grating has been calculated in order to satisfy the volume condition ($Q=10$): 2.5 μm for 750 mm^{-1}; 7.7 μm for 440 mm^{-1}; 21.7 μm for 300 mm^{-1}; and 28.0 μm for 230 mm^{-1}. We can see that for the 750 mm^{-1} grating the difference in diffraction efficiency between two polarization states and corresponding PDL is too high (about 20% or 1 dB at 1.55 μm).

In addition, its spectral uniformity over the band 1.5–1.6 μm is insufficient. This grating was therefore rejected.

For the three remaining gratings, Fig. 6 shows the variation of diffraction efficiency for the TE polarization with index modulation under Bragg conditions for fixed gratings thicknesses.

We know that a higher spatial frequency and a low thickness give a good trade-off between diffraction efficiency and spectral bandwidth, but the required value of Δn has to be realistic. For example, in the case where the thickness T just satisfies the Q≈10 condition, the refractive index modulation required for spatial frequency 440 mm^{-1} is equal to 0.08 [Fig. 6(a)]. This value is very high for traditional holographic phase materials. It can be reached only with dichromated gelatin with extremely well controlled process parameters, which complicates industrial

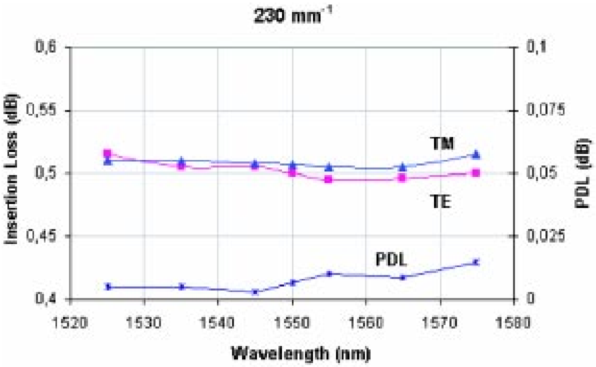

Fig. 8 Insertion loss for the 230 mm^{-1} grating at the Bragg angle for both polarization states.

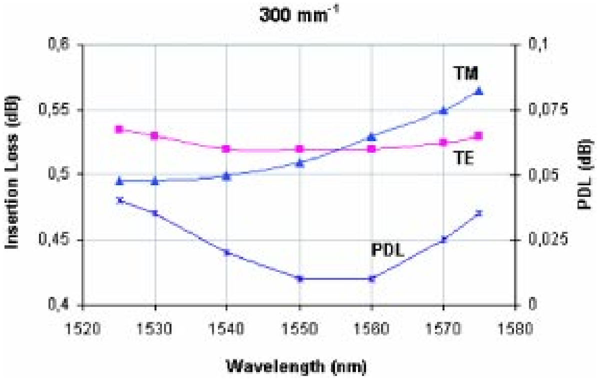

Fig. 9 Insertion loss for the 300 mm^{-1} grating at the Bragg angle for both polarization states.

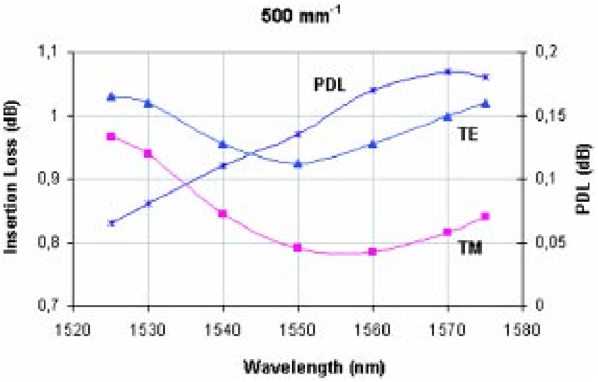

Fig. 10 Insertion loss for the 500 mm^{-1} grating at the Bragg angle for both polarization states.

production. According to the second set of curves [Fig. 6(b)], a thickness of 25 μm requires modulations of the order of 0.03, which are easier to reach.

Figures 5 and 6 show that for both polarizations, the diffraction efficiency (DE) can reach 100% but the TM polarization's maximum is shifted to short wavelengths compared to TE polarization and the refractive index modulation needed for DE optimization is not the same. Consequently, there is a simple technique to improve significantly the spectral uniformity and polarization dependent loss for transmission VPH gratings, if for the central wavelength the refractive index modulation is chosen to have the same values of DE for both polarization states.

Figure 7 illustrates this possibility. It shows the spectral response of these three gratings over the C band with a constant thickness of 25 μm, which is a standard thickness for DCG layers (PFG-04 from "Slavich") used in grating production. The refractive index modulation for each grating was calculated to give the same diffraction efficiency for both polarizations at the central wavelength (1.55 μm).

We can see clearly that the three parameters (IL, PDL, and WDL) are best for ν=300 mm^{-1} and ν=230 mm^{-1}.

5 Experimental Results with Volume-Phase Holographic Gratings

Despite the fact that the development process is complex, dichromated gelatin (DCG) is the most commonly used material for industrial applications of volume-phase gratings. We present here experimental results obtained for three volume-phase holographic gratings recorded in standard dichromated gelatin layers with a thickness T of 25 μm (with spatial frequencies of 230, 300, and 500 mm^{-1}).

Despite the simulation results, a spatial frequency of 500 mm^{-1} was chosen to illustrate in practice the importance of the trade-offs given in Sec. 3.3.2. This spatial frequency is at the limit of the required characteristics if we refer to the simulation results. We will see in the following that such a choice would have degraded considerably the performance of the system.

All gratings were studied over the C band for both TE and TM polarizations. We give spectral curves in the telecommunications context (insertion loss instead of diffraction efficiency and PDL for polarization sensitivity). The 230 mm^{-1} (Fig. 8) and 300 mm^{-1} (Fig. 9) gratings show high diffraction efficiency (close to 90%), high spectral flatness, and low PDL. However, for the 500 mm^{-1} grating (Fig. 10) all required characteristics are slightly increased. For example, average diffraction efficiency for this grating varies between 79.5% and 82%, which gives us insertion loss of about 1 dB. Table 2 shows the main characteristics for each grating.

These gratings were tested not only for Bragg incidence but also for small mismatches of the Bragg condition (Figs. 11, 12, and 13) to estimate angular tolerances. We can see that angular tolerances for the 500 mm^{-1} grating are considerably reduced.

As a conclusion, the 300 mm^{-1} grating seems to give a better trade-off over the parameters IL, WDL, and PDL as well as dispersion. Such a grating would be entirely suitable for a DSE application. This grating was tested under thermal Telcordia tests. Figure 14 shows the variations in average insertion loss for different temperatures.

6 Conclusion

Design of a diffraction grating destined for dynamic spectral equalization functions in telecommunication has been presented. The configuration of the system defines the type of grating to be used. In addition, the grating has to satisfy telecommunications criteria such as low insertion loss (IL), wavelength dependent loss (WDL), polarization dependent

Table 2 Grating characteristics from a telecommunications viewpoint and performance comparisons.

Parameter	230 mm^{-1}		300 mm^{-1}		500 mm^{-1}	
IL	+++	~0.5 dB or 89%	+++	~0.5 dB or 89%	+	~0.9 dB or 82%
WDL	+++	<0.025 dB	+++	<0.05 dB	+	>0.1 dB
PDL	+++	<0.025 dB	+++	<0.05 dB	+	>0.1 dB
Dispersion	+	0.234 deg/μm	++	0.308 deg/μm	+++	0.542 deg/μm

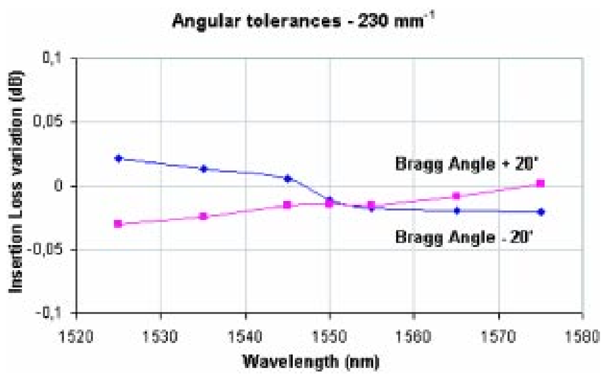

Fig. 11 Average insertion loss variation for the 230 mm^{-1} grating when detuned from the Bragg condition.

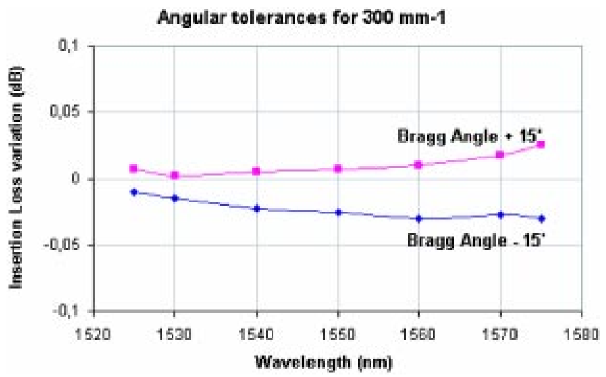

Fig. 12 Average insertion loss variation for the 300 mm^{-1} grating when detuned from the Bragg condition.

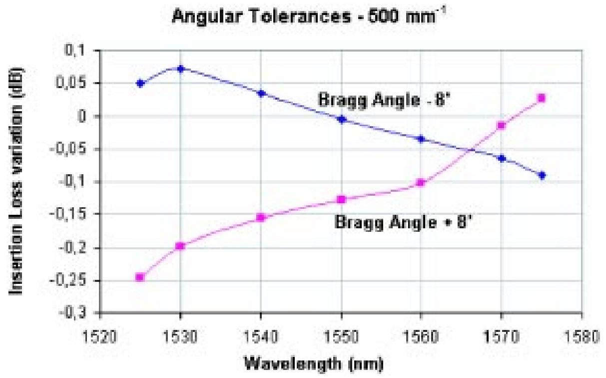

Fig. 13 Average insertion loss variation for the 500 mm^{-1} grating when detuned from the Bragg condition.

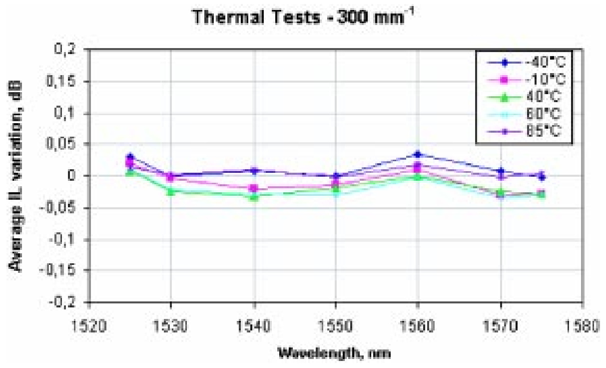

Fig. 14 Thermal tests realized over the C band for the 300 mm^{-1} grating.

loss (PDL), and dispersion constraints. Other parameters such as the angular selectivity allow the designer to flag mechanical constraints.

Generally, surface relief gratings are chosen for such applications. We have shown in this paper that a volume-phase holographic grating can satisfy all of the telecommunications requirements. The first task was to identify the different trade-offs involved for such a grating in the given application context. The simulation results allowed us to underline these trade-offs and to optimize them by choosing a suitable grating.

The method described here was then validated by experimental results, which show that volume-phase holographic gratings with a pertinent design are suitable for use as dispersive elements in a telecommunications spectral equalizer. System constraints (insertion loss, polarization dependent loss, etc.) as well as industrial constraints such as thermal tests are satisfied.

References

1. J. P. Laude, *DWDM Fundamentals, Components, and Applications*, Artech House, New York (2002).
2. J. P. Laude et al., ''Wavelength-selective multiplexer-demultiplexer,'' U.S. Pat. No. 4622662 (1986).
3. R. Ramaswami and K. N. Sivarajan, *Optical Networks: A Practical Perspective*, 2nd ed., Morgan Kaufmann, San Francisco (2002).
4. D. Q. Chowdhury, ''Diffraction grating with reduced polarization sensivity,'' U.S. Pat. No. 6097863 (2000).
5. J. Hoose, ''Optical diffraction grating structure with reduced polarization sensivity,'' U.S. Pat. No. 2001/0046087 A1 (2001).
6. A. D. Sappey and B. W. Bach, ''Apparatus and method for the reduction of polarization sensitivity in diffraction gratings used in fiber optic communications devices,'' U.S. Pat. No. 6,400,509 (2002).
7. L. Fabiny, T. Sarto, L. Muller, K. E. Arnett, and K. S. Jo Pister, ''Diffraction grating with reduced polarization-dependent loss,'' Int. Pat. No. WO 02/06860 (2002).
8. M. N. Sokolskiy, R. H. Dueck, and G. G. Capiello, ''Diffraction grating for wavelength division multiplexing/demultiplexing devices,'' Int. Pat. No. WO 019499 (2001).
9. S. C. Barden, J. A. Arns, W. S. Colburn, and J. B. Williams, ''Volume-phase holographic gratings and the efficiency of three simple volume-phase holographic gratings,'' *Astron. Soc. Pac. Conf. Ser.* **112**, 809–820 (2000).
10. A. Bianco, P. Molinari, G. Crimi, E. Giro, F. P. Pernechele, and C. Zerbi, ''VPHG in the cold,'' *Proc. SPIE* **4842**, 22–30 (2003).
11. G. M. Bernstein, A. E. Athey, R. Bernstein, S. M. Gunnels, D. O. Richstone, and S. A. Shectman, ''Volume-phase holographic spectrograph for the magellan telescopes,'' *Proc. SPIE* **4485**, 453–459 (2002).
12. W. Yang and S. Zhang, ''Compact double-pass wavelength multiplexer-demultiplexer having an increased number of channels,'' U.S. Pat. No. 6,108,471 (2000).
13. W. Yang and S. Zhang, ''Compact double-pass wavelength multiplexer-demultiplexer,'' U.S. Pat. No. 6,275,630 (2001).
14. J. A. Arns and W. S. Colburn, ''Polarization insensitive, high dispersion optical element,'' U.S. Pat. No. 6,449,066 B1 (2002).
15. H. Kogelnik, ''Coupled wave theory for thick hologram gratings,'' *Bell Syst. Tech. J.* **48**(9), 2909–2947 (1969).
16. M. G. Moharam and T. K. Gaylord, ''Three-dimensional vector coupled-wave analysis of planar grating diffraction,'' *J. Opt. Soc. Am. A* **73**(9), 1105–1112 (1983).
17. M. G. Moharam, E. B. Grann, D. A. Pommet, and T. K. Gaylord, ''Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings,'' *J. Opt. Soc. Am. A* **12**(5), 1068–1076 (1995).
18. C. G. Stojanoff, H. Schuette, and P. Froening, ''Evaluation of holographis materials from an applications point of view,'' *Proc. SPIE* **3294**, 2–13 (1998).
19. C. W. Chen and E. W. Gossett, ''Grism (grating-prism combination),'' U.S. Pat. No. 5,652,681 (1997).
20. C. W. Chen, ''Achromatic and apochromatic prism element employing prisms and gratings,'' U.S. Pat. No. 5,625,499 (1997).