

Gratings superposed spatially by writing in laterally separated regions

Thomas L. Gradishar

*Florida Communication Research Lab, Motorola Labs
8000 W. Sunrise Blvd, Room 2141, Plantation FL 33322
Tom.Gradishar@motorola.com*

A. Safaai-Jazi

*Bradley Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0111
Ajazi@vt.edu*

Abstract: A new type of gratings superposed spatially in laterally separated areas of the guide is introduced and analyzed using coupled-mode theory. The guided mode overlaps the constituent gratings and sees the superposition of them. Also, special characteristics that the structure might synthesize are considered, including one example where a phase-only sampled split grating provides zero response for out-of-band channels. A conventional grating requires both phase- and amplitude- sampling for zero out-of-band channels. The split grating, however, requires alignment of the constituent gratings in addition to requirements on the accuracy of the amplitude and pitch structures.

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1. Introduction

Superposed Bragg gratings in fiber or planar optical waveguides have found use in multi-channel filters and dispersion compensators [1-3], sensors [4,5], and for generating high-repetition-rate pulse trains [6]. The gratings are superposed on top of each other in the same volume as the UV beam is scanned to write the grating. In this work an alternate method for superposing gratings is introduced where parallel constituent gratings are superposed spatially in different areas of the guide. This new type of grating was recently proposed by the authors with the aim of exploring the properties of gratings with independently apodized layers [7]. The guided mode overlaps the constituent gratings and sees the superposition of them. The constituent gratings have the same central pitch but separate phase- and amplitude modulations.

A coupled-mode analysis of the structure is presented. Then special characteristics that the structure might provide are considered. An example of special characteristics is given where a split grating, comprising 2 phase-only sampled constituent gratings, provides zero reflectivity for out-of-band channels. A conventional grating requires amplitude-sampling in addition to phase-sampling to provide zero reflectivity for out-of-band channels [8-10]. Sampling refers to modulation of the refractive index profile along the guide by a periodic sampling function. With phase-only sampling the sampling function has only a varying phase.

Recently a spatially superposed grating was implemented experimentally using femtosecond inscription in a fiber core [11]. One constituent grating is confined in a fraction of the fiber core, while a second is inscribed in the same length of fiber in a non-overlapping fraction of the core. While this demonstrates that in principle implementing a structure like in this paper is possible, the analysis here is for gratings written in photosensitized guides. To extend the analysis to gratings written with femtosecond inscription, the coupling to cladding modes and other effects that occur would have to be modeled.

2. Basic features of the structure

The spatially superposed gratings might be formed by separately exposing fractions of the waveguide through phase masks. One fraction of the waveguide is exposed while an opaque mask covers the remaining portions. Then a different fraction of the waveguide in parallel with the first at a lateral offset, and over the same length of guide, is exposed through a different phase mask, although with the same central pitch. Alignment between the constituent gratings in terms of grooves of the phase mask is crucial, as for example in Fig. 1 where the grooves are at a 180-degree phase offset.

The coupled mode analysis of the next section assumes for simplicity a slab guide having one photosensitized layer, of the form

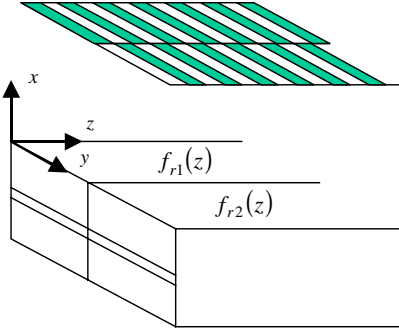


Fig. 1. Slab waveguide written with spatially superposed gratings.

$$n(x, y) = \begin{cases} n_1 & -a < x < 0, \quad 0 < y < b \\ n_2 & \text{otherwise} \end{cases} \quad (1)$$

As usual in coupled-mode analysis the refractive index of the grating is written in terms of an unperturbed guide and a refractive index perturbation as

$$n'(x, y, z) = n(x, y) + \Delta n(x, y, z) \quad (2)$$

where the perturbation, i.e. refractive index change, is given by, assuming 4 constituents

$$\Delta n(x, y, z) = f_{ri}(z) \left[1 + \cos \left(\frac{2\pi z}{\Lambda} + \phi_{ri}(z) \right) \right] \quad (3)$$

for $-a < x < 0$ and $(i-1)b/4 < y < ib/4$; $i = 1, 2, 3, 4$.

Every constituent grating is with the same central pitch, Λ , but on the other hand different apodization and phase modulation, $f_{ri}(z)$ and $\phi_{ri}(z)$. Equation (3) is written assuming the “dc” index change, the index change spatially averaged over one grating period, is proportional to the “ac” index change. Note however that a fabrication method might also provide a constant or zero “dc” index change.

3. Coupled-mode analysis

The spectral and dispersive properties of the split structure are analyzed using coupled-mode theory. For simplicity, the waveguide is assumed to have a width many times larger than its thickness, hence a two-dimensional guide is a good model. Also, only coupling between a single mode and a like counter-propagating mode is considered.

Coupled-mode theory provides a coupled pair of differential equations for the amplitudes as can be written, considering only the forward and backward traveling modes, as [12]

$$\frac{d\psi_1}{dz} = j(\psi_1 C_{11} + \psi_2 e^{-j2\beta z} C_{12}) \quad (4a)$$

$$\frac{d\psi_2}{dz} = j(\psi_2 C_{22} + \psi_1 e^{j2\beta z} C_{21}) \quad (4b)$$

where $\psi_1(z)$ and $\psi_2(z)$ are slowly varying amplitudes of the forward and backward traveling modes respectively, and C_{km} ; $k, m = 1, 2$, are the coupling coefficients given by

$$C_{km}(z) = \frac{\omega \epsilon_0}{4} \text{sgn}(\beta_k) \int_S (n'^2 - n^2) \mathbf{e}_k^* \cdot \mathbf{e}_m ds \quad (5)$$

with $\text{sgn}(\beta_1) = \text{sgn}(\beta) = 1$ and $\text{sgn}(\beta_2) = \text{sgn}(-\beta) = -1$. The integral in Eq. (5) is over the cross-section of the waveguide (xy- plane) and \mathbf{e}_k and \mathbf{e}_m are such that $\mathbf{E} = \mathbf{e}_1(x)\exp(j\beta z)$ and $\mathbf{E}_- = \mathbf{e}_2(x)\exp(-j\beta z)$ represent the normalized fields of the forward and backward traveling modes, respectively. With normalized fields, the power of each mode is unity. Inserting Eq. (3) into the following approximation,

$$n'^2 - n^2 \approx 2n(x, y)\Delta n(x, y, z), \quad \Delta n(x, y, z) \ll n(x, y) \quad (6)$$

the coupling coefficients are written as

$$C_{11}(z) = \sigma(z) + \exp\left(j\frac{2\pi z}{\Lambda}\right)K_{SA}(z) + \exp\left(-j\frac{2\pi z}{\Lambda}\right)K_{SA}^*(z) \quad (7a)$$

where

$$K_{SA}(z) = \sum_{i=1}^4 K_{ri}(z) \exp[j\phi_{ri}(z)] \quad (7b)$$

$$\sigma(z) = 2 \sum_{i=1}^4 K_{ri}(z) \quad (7c)$$

$$K_{ri}(z) = \frac{\omega \epsilon_0 n_1}{4} f_{ri}(z) \int_{b_i}^{b_{i+1}} \int_{-a}^0 \mathbf{e}_1^* \cdot \mathbf{e}_1 dx dy \quad (7d)$$

and $b_i = (i-1)b/4$, $i=1, \dots, 4$. Under the 2-D guide assumption the width of the guide, b , cancels out of the equations since the integral over dy cancels with $1/b$ that occurs with normalizing the fields. Though Eq. (7a) is for $C_{11}(z)$ it can be shown that

$$C_{21}(z) \approx C_{22}(z) \approx -C_{11}(z) \approx -C_{12}(z) \quad (8)$$

where the negative signs are due to $\text{sgn}(\beta_k)$ in Eq. (5). Eq. (8) is valid if the modes correspond to TE_0 because $\mathbf{e}_1 = \mathbf{e}_2$. Alternatively, if they correspond to TM_0 and the guide is weakly guiding, it still is true that $\mathbf{e}_1 \approx \mathbf{e}_2$ since $\mathbf{e}_{1z} \ll \mathbf{e}_{1x}$ in $\mathbf{e}_2 = \mathbf{e}_{1x} - \mathbf{e}_{1z}$.

Besides Eq. (3) another form the perturbation might take is the form resulting from a fabrication technique that provides "pure apodization", meaning "dc" index change that is a constant. The perturbation is given by

$$\Delta n(x, y, z) = f_{ri}(z) \cos\left(\frac{2\pi z}{\Lambda} + \phi_{ri}(z)\right) + \Delta n_{dci} \quad (9)$$

for $-a < x < 0$ and $(i-1)b/4 < y < ib/4$; $i=1, 2, 3, 4$.

where Δn_{dci} ; $i=1, 2, 3, 4$, are constants. Eqs. (4) through (8) still apply except for (7c) which is replaced by

$$\sigma(z) = \frac{\omega \epsilon_o n_1}{2} \sum_{i=1}^4 \Delta n_{dci} \int_{b_i}^{b_{i+1}} \int_{-a}^0 \mathbf{e}_1^* \cdot \mathbf{e}_1 dx dy \quad (10)$$

Substituting Eq. (7a) and Eq. (8) into the coupled equation system Eq. (4a,b) and neglecting the terms that oscillate rapidly with z relative to the amplitudes $\psi_1(z)$ and $\psi_2(z)$ gives

$$\frac{d\psi_1(z)}{dz} = j\psi_1(z)\sigma(z) + j\psi_2(z) \exp\left[-j\left(2\beta z - \frac{2\pi z}{\Lambda}\right)\right] K_{SA}(z) \quad (11a)$$

$$\frac{d\psi_2(z)}{dz} = -j\psi_2(z)\sigma(z) - j\psi_1(z) \exp\left[j\left(2\beta z - \frac{2\pi z}{\Lambda}\right)\right] K_{SA}^*(z) \quad (11b)$$

This coupled pair of differential equations has variable coefficients, so an analytical solution usually is not available. Numerical methods are available for computing a solution including direct numerical integration and a piecewise-uniform approach [12].

The reverse problem is of interest where the desired responses are given and index changes of the split grating that produce them are sought. The desired responses might be ones that can also be produced with a conventional grating. In this case, an approach is with first finding a conventional grating that provides the responses, then splitting its index change in two terms. The split grating provides the same responses as the conventional grating, only with different characteristics in terms of the amplitude and pitch structures. The other situation is where the split grating provides special performance characteristics in terms of the responses themselves, i.e. responses that would be difficult to obtain using a conventional (unsplit) grating.

For the first situation, where the split grating duplicates the responses of a given unsplit grating, two examples are presented below. In the first the split grating is phase-only sampled, while the unsplit grating (that the split grating imitates) is both phase- and amplitude sampled. In the second example the split grating is amplitude-only sampled while the unsplit grating has numerous π phase-shifts. For both examples, since the intention is to reproduce the responses of a conventional grating, the split grating should reproduce its “ac” coupling coefficient. If the split grating has symmetry where it comprises only 2 constituent gratings, and the boundary between them is the centerline of the guide, the integral over the fields incorporated in the “ac” coupling coefficient cancels with the one for the conventional grating. Thus we choose this symmetric split grating for the examples. With this symmetric split grating, setting the “ac” coupling coefficient equal to that of the conventional grating leads to

$$\Delta n_{uac}(z) = f_u(z) \cos\left(\frac{2\pi z}{\Lambda_u} + \phi_u(z)\right) = 0.5 \sum_{i=1}^2 f_{ri}(z) \cos\left(\frac{2\pi z}{\Lambda} + \phi_{ri}(z)\right) \quad (12)$$

where the left-hand side is the “ac” part of the index change of the unsplit grating, and $f_u(z)$ and $\phi_u(z)$ are the index modulation and phase, where u stands for unsplit. The right hand side is one-half the sum of the “ac” index changes in the constituent gratings. Whether the index change of the split grating has the form of Eq. (3) or (9), the “ac” part has the form seen in the right-hand side of Eq. (12). Eq. (12) was found by setting the “ac” coupling coefficient of the conventional grating, given by

$$K_{SA}(z) = \frac{\omega \epsilon_o n_1}{4} f_u(z) \exp[j\phi_u(z)] \int_0^b \int_{-a}^0 \mathbf{e}_1^* \cdot \mathbf{e}_1 dx dy \quad (13)$$

equal to the “ac” coupling coefficient of the split grating, given by Eq. (7b,d). The integrals over the fields in the left- and right-hand sides of the equation cancel due to the symmetry of the split grating, leaving the factor 0.5 in the right-hand side of Eq. (12).

The split grating is formed by one scan that writes into $y < b/2$ and a different one that writes into $y > b/2$. What if the two scans instead write into the entire volume $0 < y < b$ and thus overwrite the same volume of material? Eq. (12) states that the “ac” coupling coefficient is the same. The grating formed by overwriting the 2 scans has the same “ac” coupling coefficient, and thus can provide the same responses. The 2 scans should be modified by cutting the light intensity by a factor of 2, but otherwise not modified (in terms of the profile of the light intensity.) Thus for the split grating with the pair of constituent gratings with the centerline as the boundary there is no difference in terms of responses compared to overwriting the scans on top of each other.

For the split grating to produce the same responses as the conventional one, reproducing the “ac” coupling coefficient of the conventional grating is one requirement, but the split grating should also reproduce the “dc” coupling coefficient. Alternatively, if the split and conventional gratings both are fabricated using a pure apodization method then the “dc” coupling coefficients are both constants. In this case the “dc” coupling coefficient of the split grating does not have to equal that of the conventional one. The “dc” coupling coefficient is incorporated in the coupled-mode equations in the same term as the grating central pitch, thus the central pitch can be tailored to compensate for the value of the “dc” coupling coefficient of the split grating, whatever it might be.

4. Example: phase-only sampled split grating

For generating a uniform band of channels one approach is amplitude sampling, as with rect- and sinc-sampled gratings [13]. Another approach is phase-only sampling, which has attracted interest because accurately positioning grooves on the phase mask can easily be implemented using advanced lithographic tools [14,15]. However, phase-only sampling cannot achieve zero reflectivity for out-of-band channels, and for this some authors have presented gratings with phase as well as amplitude sampling [8-10]. The sampling function has varying amplitude as well as varying phase.

A uniform band of channels with zero reflectivity for out-of-band-channels can also be achieved with a split grating. In the example here, the split grating comprises two phase-only sampled constituent gratings. Thus, with only phase-sampling the split grating achieves zero reflectivity for out-of-band channels.

Such a split grating can be derived by picking the unsplit grating it will imitate, then splitting the index change of that grating into 2 constant-envelope terms and assigning them to the split grating. This is the approach used here. First, to pick the unsplit grating that will be imitated, it must provide zero reflectivity for out-of-band channels. Also the maximum of the index change is preferably as small as possible. Considering these 2 requirements we are picking the sampling function of the form found in [8,9] given by

$$s(z) = \sum_{m=-4}^4 \exp(j\phi_m) \exp\left(\frac{j2m\pi z}{P}\right) \quad (14)$$

for $N=9$ channels, where ϕ_m is the phase of the m-th channel and P is the sampling period. A sampling function having this form intrinsically provides zero reflectivity for out-of-band channels. For minimizing the index change the authors provide optimization techniques where the ϕ_m are optimized in order to minimize the peak value of the sampling function. In [8] it is a more heuristic approach while in [9] it is with solving a mini-max problem. Here we are combining them by using the coefficients which the authors of [8] have found for $N=9$ channels, and using them as the initial estimate in the mini-max problem. We

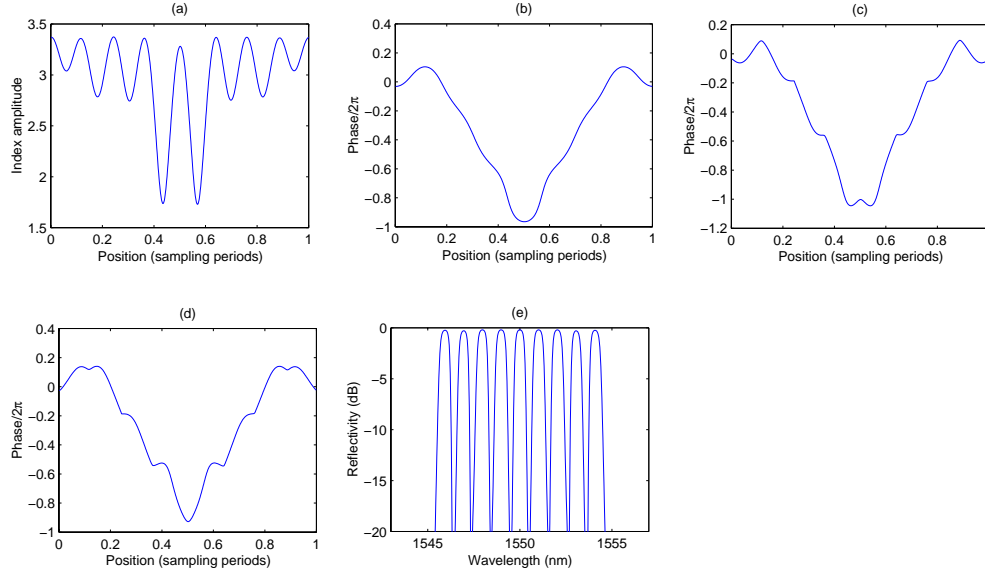


Fig. 2. Sampling functions of unsplit and equivalent split gratings. Sampling function $s(z) = a(z)\exp[j\phi(z)]$ of the unsplit grating. (a) Amplitude $a(z)$ and (b) normalized phase $\phi(z)/2\pi$. Sampling functions of the split grating. (c) Normalized phase in the volume $y < b/2$ and (d) in $y > b/2$. (e) Nine channel reflectivity response.

used the Matlab `fminimax` function found in the Optimization Toolbox. The initial estimate is (copied from [8])

$$\phi_m = [5\pi/3, \pi, \pi/3, 0, 0, 0, \pi/3, \pi, 5\pi/3]. \quad (15)$$

Starting with this initial estimate `fminimax` optimized the ϕ_m . Putting the computed ϕ_m in Eq. (14) the magnitude and phase are shown in Fig. 2. The computed ϕ_m are only moderately different than the initial estimate, indicating the closeness of that estimate to a mini-max solution. The theoretical limit on the peak value of the sampling function is \sqrt{N} [9,15]. In Fig. 2 the peak is 3.4, which is 13% higher than the limit. Finally, the index change is given by [8,15]

$$\Delta n(z) = \text{Re} \left\{ f(z) \exp \left[j \left(\frac{2\pi z}{\Lambda_u} + \phi_g(z) \right) \right] s(z) \right\} \quad (16)$$

where a single-channel seed grating is with the index modulation $f(z)$, the central pitch Λ_u , and the phase $\phi_g(z)$.

Turning now to the split grating, we assume it has the symmetry described above where the constituent gratings occupy $y < b/2$ and $y > b/2$. Thus the index changes should be related to that of the conventional grating per Eq. (12). As this equation suggests, the index change, or equivalently the sampling function, of the conventional grating can be divided into a pair of terms, which the split grating then receives. These must be constant envelope since the goal is for the constituent gratings to be phase-only sampled. In other words, constant envelope terms should sum to (14). This is the same problem as with LINC radio systems where a non-constant envelope signal is split into two phase-modulated constant envelope signals [16].

Writing the sampling function of the original as $s(z) = a(z)\exp[j\phi(z)]$ where the amplitude $a(z)$ has a maximum value A , the terms are (as with LINC)

$$s_1(z) = \frac{A}{2} \exp \left[j \left(\phi(z) - \cos^{-1} \left(\frac{a(z)}{A} \right) \right) \right] \quad \text{for the volume } y < b/2 \quad (17a)$$

$$s_2(z) = \frac{A}{2} \exp \left[j \left(\phi(z) + \cos^{-1} \left(\frac{a(z)}{A} \right) \right) \right] \quad \text{for the volume } y > b/2 \quad (17b)$$

Figure 2 plots the phases of these constant envelope sampling functions. For fabricating this split grating the accuracy of the pitch structures would be crucial, even in terms of the difference in phase between them. With these sampling functions the constituent gratings have the index changes

$$\Delta n_1(z) = 2 \operatorname{Re} \left\{ f(z) \exp \left[j \left(\frac{2\pi z}{\Lambda} + \phi_g(z) \right) \right] s_1(z) \right\} \quad \text{for the volume } y < b/2 \quad (18a)$$

$$\Delta n_2(z) = 2 \operatorname{Re} \left\{ f(z) \exp \left[j \left(\frac{2\pi z}{\Lambda} + \phi_g(z) \right) \right] s_2(z) \right\} \quad \text{for the volume } y > b/2 \quad (18b)$$

The seed grating is the same as with the original grating, i.e., with $f(z)$ and $\phi_g(z)$. The factors of 2 are for counteracting the factor 0.5 in (12). Thus the left- and right-hand sides of Eq. (12) are equal, and the conventional and split gratings have the same reflectivity responses. Due to the factors of 2 the maximum index change equals, though at least it does not exceed, the maximum index change of the conventional grating. Figure 2 shows the reflectivity, assuming a seed grating with a bell-shaped apodizing function and $\phi_g(z) = 0$.

The slab waveguide has $a_1 = 0.15 \mu\text{m}$, $n_1 = 1.4579$, and $n_2 = n_{\text{SiO}_2}$. Finally, note that the reflectivity for out-of-band channels is zero.

5. Example: amplitude-only sampled split grating

In this example, like in the previous one, a split grating provides the same responses as a conventional grating. Like in the previous example the conventional grating is both amplitude- and phase-sampled, and multi-channel with zero reflectivity for out-of-band channels. Unlike the previous example, however, the constituent gratings of the split grating are amplitude-only sampled.

The sampling function of the conventional grating that will be imitated is of the same form as in the last example although with only 4 channels

$$s(z) = \sum_{m=1}^4 \exp(j\phi_m) \exp \left(\frac{j 2(2m-5)\pi z}{P} \right) \quad (19)$$

Furthermore, almost the same procedure is used to optimize the channel phases, ϕ_m . The one difference is this time a symmetry for the channel phases will be enforced in order to produce a sampling function that's purely real. Splitting this purely real sampling function into a pair of purely real terms will then be trivial, and thus the constituent gratings will be amplitude-only modulated which is the goal. The symmetry enforced is

$$\phi_1 = -\phi_4, \quad \phi_2 = -\phi_3 \quad (20)$$

Calculating the coefficients with fminimax the sampling function that was obtained is shown in Fig. 3. The coefficients are $\phi_3 = 4.7124$ and $\phi_4 = 10.9956$. The max value is 3.08, or

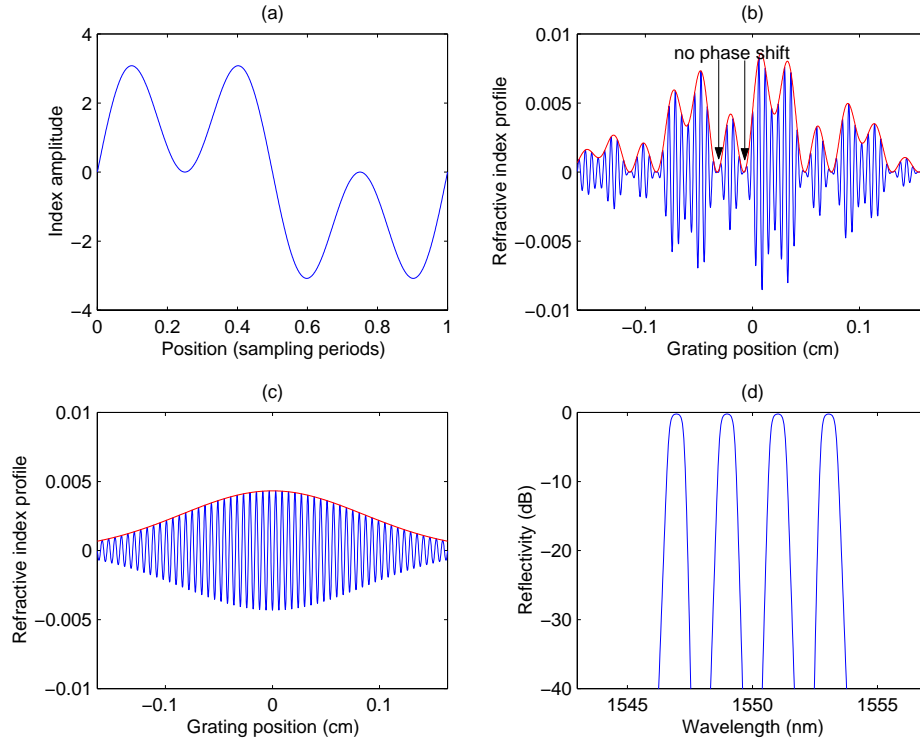


Fig. 3. Sampling functions of an unsplit grating and equivalent split grating. For the unsplit grating (a) the pure-real sampling function. For the split grating (b) profile of the index change (red curve) and index change itself (blue curve) in the volume $y < b/2$ versus position along the grating (four sampling periods are shown.) (c) Profile and index change in the volume $y > b/2$. (d) Four channel reflectivity response.

about 1.5 times the theoretical minimum value of \sqrt{N} , which is not as close to the limit as in the prior example, which can be attributed to the Eq. (20) constraint. Note that it includes two sign changes. It can be shown that with picking channel phases under the Eq. (20) constraint sign changes are unavoidable. (The procedure in [9] for eliminating sign changes is for the case where, besides sign changes, the phase varies continuously. In other words it's for the case where the sampling function is complex.) Thus, to fabricate the grating with this sampling function, the points where there are sign changes, i.e., π phase shifts, in the sampling function require inserting one-half a local grating period [13].

Turning now to the split grating, it will receive sampling functions found by spitting the above sampling function into a pair of terms. Since the goal is amplitude-only modulation, without even phase shifts, the terms should be purely real and without sign changes. An obvious solution is

$$s_1(z) = 3.08 + s(z) \quad \text{for the volume } y < b/2 \quad (21a)$$

$$s_2(z) = -3.08 \quad \text{for the volume } y > b/2 \quad (21b)$$

The grating in $y > b/2$ has only a "dc" sampling function, equal to the minimum of the sampling function of the conventional grating (seen in Fig. 3(a)). With this constituent grating since the sampling function is a constant it is not actually sampled, since the sampling function represents only a multiplicative gain factor for the seed grating. With the above sampling functions, the index changes of the split grating are

$$\Delta n_1(z) = 2f(z)s_1(z) \cos\left(\frac{2\pi z}{\Lambda} + \phi_g(z)\right) \quad \text{for the volume } y < b/2 \quad (22a)$$

$$\Delta n_2(z) = 2f(z)|s_2(z)| \cos\left(\frac{2\pi z}{\Lambda} + \phi_g(z) + \pi\right) \quad \text{for the volume } y > b/2 \quad (22b)$$

where the π phase offset of the $y > b/2$ grating (π shift with respect to the $y < b/2$ grating) is due to the negative sign in $s_2(z)$. The sum of these index changes equals 2 times the perturbation of the conventional grating. Thus Eq. (12) holds, and thus the split grating provides the same responses as the conventional grating.

The first constituent grating is similar to the original grating in terms of complexity of the amplitude modulation but is free of the π phase shifts. Figure 3(b) shows the index change and its profile over four sampling periods. The other constituent grating has only a bell-shaped profile without sampling, as contemporary grating writing techniques can routinely create. Figure 3 shows the index change and profile of this constituent grating as well. The reflectivity of the original grating and the split grating (they are identical in reflectivity) is shown in Fig. 3(d) assuming the same seed grating and unperturbed waveguide as in the prior example.

6. Conclusions

With superposing spatially, different gratings are written in non-overlapping areas of the guide, as opposed to overwriting the same volume of material. The guided mode overlaps the constituent gratings and sees the superposition of them. A coupled mode analysis was presented for the structure.

A symmetric split grating was presented where the constituent gratings are each written in one-half the guide, i.e., the centerline is the boundary. In this case the integral over the fields for computing the coupling coefficients is the same for constituent grating #1 as for #2. Furthermore it's one-half the value with integrating over the entire cross-section of the guide. Instead of one scan that writes constituent grating #1 and a second scan that writes #2 in the other half of the material, the 2 scans could overwrite the same volume of material. The resulting conventional (unsplit) grating would have the same responses as the split one. Thus for the split grating with the pair of constituent gratings with the centerline as the boundary there is no difference in terms of responses compared to overwriting the scans on top of each other. Note however this is not like typical overwriting, since for each scan the perturbation has the same central pitch.

An example was given where the structure comprises 2 constituent gratings, each phase-only sampled. It provides a band of 9 uniform channels, with zero reflectivity for out-of-band channels. With a conventional (unsplit) grating with phase-only sampling zero reflectivity for out-of-band channels is not possible.

A second example was given where the structure comprises 2 constituent gratings, one of which is amplitude-only sampled without sign changes. The other is not sampled, rather it has a bell-shaped profile as contemporary grating writing techniques can routinely create. With a conventional (unsplit) grating with amplitude-only sampling, sign-changes in the sampling function are unavoidable. To fabricate the conventional grating, each point where there is a sign change requires inserting one-half a local grating period.

Note that in these 2 examples the split grating has the symmetry described above where the centerline is the boundary between constituent gratings, thus the conventional grating that would be created by overwriting the scans would provide the same reflectivity and dispersion responses. It can be said the split gratings have special characteristics in terms of the amplitude and pitch structures, but not in terms of the responses. If the split grating is not symmetric the situation is different in that there is no conventional grating that could precisely

reproduce the responses. In terms of responses, special performance characteristics that might be obtained with the split structure would be with the asymmetric version.