SIMULATION OF PERIODICALLY SEGMENTED WAVEGUIDES AS CONCURRENT BRAGG REFLECTORS AND QUASI-PHASE-MATCHED SECOND HARMONIC GENERATORS

Cangsang Zhao and Reinhart Engelmann
Department of Electrical Engineering and Applied Physics
Oregon Graduate Institute of Science & Technology
P. O. Box 91000, Portland, OR 97291-1000

Abstract

A simplified method has been developed to simulate the quasi-phase-matched (QPM) second harmonic generation (SHG) and distributed Bragg reflection (DBR) properties in a periodically segmented (PS) waveguide with graded index profiles for the purpose of designing a concurrent DBR and QPM SHG waveguide device.

I. INTRODUCTION

In the past several years QPM SHG has drawn considerable interest in the development of coherent blue or green light sources. Conversion efficiencies as high as 20% and blue light powers over 20 mW have been achieved in nonlinear crystals like lithium niobate ($LiNbO_3$) [1], lithium tantalate ($LiTaO_3$) [2], and potassium titanyl phosphate (KTP) [3]. Using semiconductor diode lasers as the sources in the QPM scheme has the potential of making compact coherent blue or green sources, and much work has been done to develop this kind of system in various crystals [2], [4], [5]. Either an optical isolator or an extended-cavity configuration using a bulk diffraction grating for feedback has to be used in the frequency doubling system to stabilize the diode laser sources, which will lead to a less compact and high cost device. A more attractive scheme of achieving coherent compact blue or green light sources is to make a concurrent QPM SHG and DBR waveguide [6], [7]. The waveguide itself then functions not only as the QPM SHG device but also as an extended-cavity mirror to stabilize the diode laser source. In the PS waveguide suitable for QPM SHG, in addition to the non-linear optical coefficient the linear optical constant (refractive index) is also periodically modulated along the propagation direction. This allows the waveguide to serve simultaneously as a distributed Bragg reflector. To achieve both QPM SHG and Bragg reflection at the same wavelength λ the QPM condition (order q):

$$(N_{\lambda/2} - N_{\lambda})\Lambda = \frac{q\lambda}{2} \qquad (q = 1, 2, \ldots, \infty) \tag{1}$$

and the DBR condition (order m):

$$N_{\lambda}\Lambda = \frac{m\lambda}{2} \qquad (m = 1, 2, \ldots, \infty) \tag{2}$$

have to be concurrently satisfied. Thus it is very critical to accurately estimate the mode indices $N_{\lambda/2}$ and N_{λ} of the periodically segmented structure in order to determine the periods Λ which satisfy both the conditions (1) and (2). It has been verified [8], [9] that in order to calculate in a PS step-index slab waveguide the effective mode index and the field distribution, one can safely replace the PS waveguide with a uniform waveguide such that its refractive index is equal to the weighted average of the high and low indices. This procedure can also be applied to a PS step-index channel waveguide [9]. But the intensity of the Bragg reflection cannot be easily derived in this approach unless a complicated numerical calculation is used [8], [9]. Also, the more realistic graded refractive index distributions in both vertical and lateral directions make it highly complicated or even impossible to find the effective mode indices and the Bragg reflection intensity in PS channel waveguides. In the following a simplified method will be presented to calculate the mode indices and the Bragg reflection intensity in order to design a device which can simultaneously satisfy DBR and QPM SHG conditions in a PS channel waveguide with more realistic graded-index distributions.

II. MODE INDEX CALCULATION CONSIDERATIONS

In principle, a PS waveguide can be viewed as a lens waveguide whose guided modes periodically diffract and refocus with negligible diffraction loss [10]. When a mode is propagating in the PS waveguide, it is locally guided or "refocused" in the high index sections, and unguided or "diffracted" in the substrate index sections and it is the guiding region which leads to the overall waveguiding. So it is reasonable to expect a homogeneous waveguide to have an equivalent guiding behavior as the PS waveguide [8], [9]. As shown in Figs. 1(a) and 1(b) for a PS step-index channel waveguide the effective mode index N can be calculated from an equivalent homogeneous step-index channel waveguide with weighted average of the high and low indices in the two sections [9]. In the high index sections the mode is guided locally as in a homogeneous step-index channel waveguide as shown in Fig. 1(c), and the local mode can be described by a mode index N_{high} calculated therefrom. But in the substrate index sections the mode is actually unguided and cannot be described by a mode index locally. In order to estimate the DBR reflectance in such a waveguide, an average index N_{low}, which describes the mode propagating speed in the substrate index sections, can be calculated from

$$N = DN_{high} + (1 - D)\, N_{low} \tag{3}$$

where D is the duty cycle of the PS waveguide. Thus the reflectance of the DBR can be calculated as in a periodically layered media with index N_{high} and N_{low} as shown in Fig. 1(d).

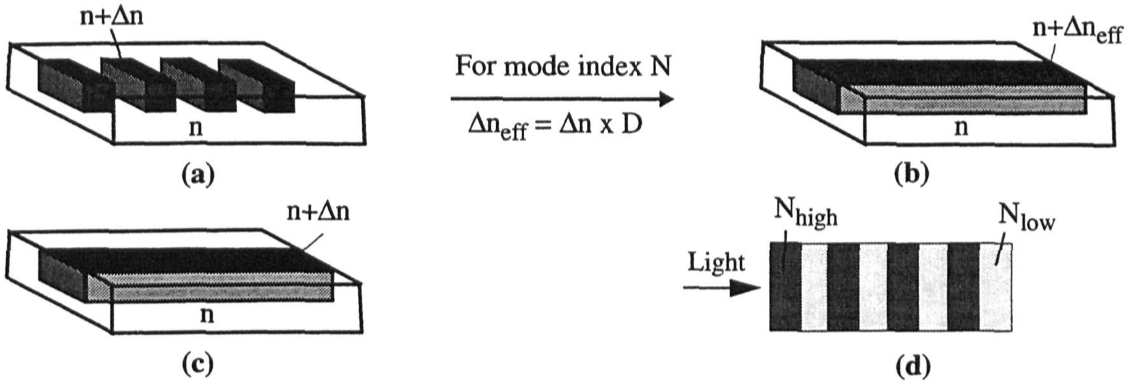

Figure 1 **(a)** Periodically segmented (PS) step-index channel waveguide; **(b)** Equivalent waveguide for calculating the mode index N; **(c)** Equivalent waveguide for calculating mode index N_{high}; **(d)** Equivalent layered media for calculating DBR properties.

For more realistic index distributions in a PS channel waveguide shown in Fig. 2(a), the mode index N_{high} can always be calculated by using the effective index method when the index profiles are given. As shown in Fig. 2(b), an equivalent step-index waveguide having the same local mode index N_{high} as in Fig. 2(a) can be found to simulate the guiding behavior in the high index sections. Thus the waveguide problem

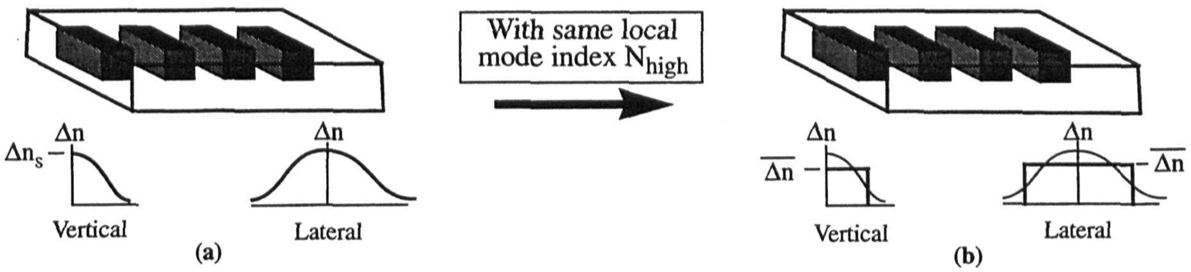

Figure 2 **(a)** Periodically segmented (PS) graded-index channel waveguide;
(b) Equivalent periodically segmented (PS) step-index channel waveguide.

reduces to a PS step-index waveguide problem, which has been solved previously. In waveguides as shown in Fig. 2(a) the index profiles are mostly Gaussian, squared hyperbolic tangent, or exponential functions, the mode index N_{high} can be calculated analytically (approximately, but accurate enough for mode index calculation). Thus the simulation of the concurrent DBR and QPM SHG device can be accomplished very rapidly and accurately.

III. RESULTS

For a KTP PS waveguide as shown in Fig. 2(a) exhibiting high-index sections with a step-index function in the lateral direction (w = 8 μm; a lateral step-index approximation is good enough when w is not too small), a squared hyperbolic tangent index function in the vertical direction (characteristic depth d = 3 μm, surface index difference $\Delta n_s = 0.016$), and a duty cycle D = 0.52, the equivalent PS step-index channel waveguide has been found with a uniform index difference $\overline{\Delta n} = 0.012$. From this result the concurrent DBR and QPM grating periods and fundamental wavelengths as shown in Fig. 3(a) have been calculated for the first order (q=1) QPM condition and various order DBR conditions. In Rb/Ba-diffused waveguides in KTP, temperature tuning allows one to shift the relative position of λ_{DBR} and λ_{QPM} by 0.051 nm/°C [11]. Consequently if one is constrained to temperature tuning of the KTP waveguide by say ± 10 °C, then, at the center of the temperature band, λ_{DBR} and λ_{QPM} should match within some 0.51 nm. This corresponds to a fabrication allowance of ± 0.005 μm deviation of the grating period from 4.202 μm according to the enlarged plot shown in Fig. 3(b) for m=18 and q=1. At the intersection point, the calculated material index n is 1.840, and the effective mode index N is 1.842, N_{high} and N_{low} are 1.847 and 1.837 respectively, which are used to calculate the DBR reflectance as shown in Fig. 3(c). An interesting behavior of the waveguide especially from a device design point of view is shown in Fig. 3(d). By choosing three different Δn_s = 0.01, 0.015, and 0.02, and varying the duty cycle from 0.5 to 0.75, one can choose the preferable wavelengths in a relatively wide range of about 10 nm. The refractive index data used above is obtained from previously reported index measurements on hydrothermally grown KTP [12].

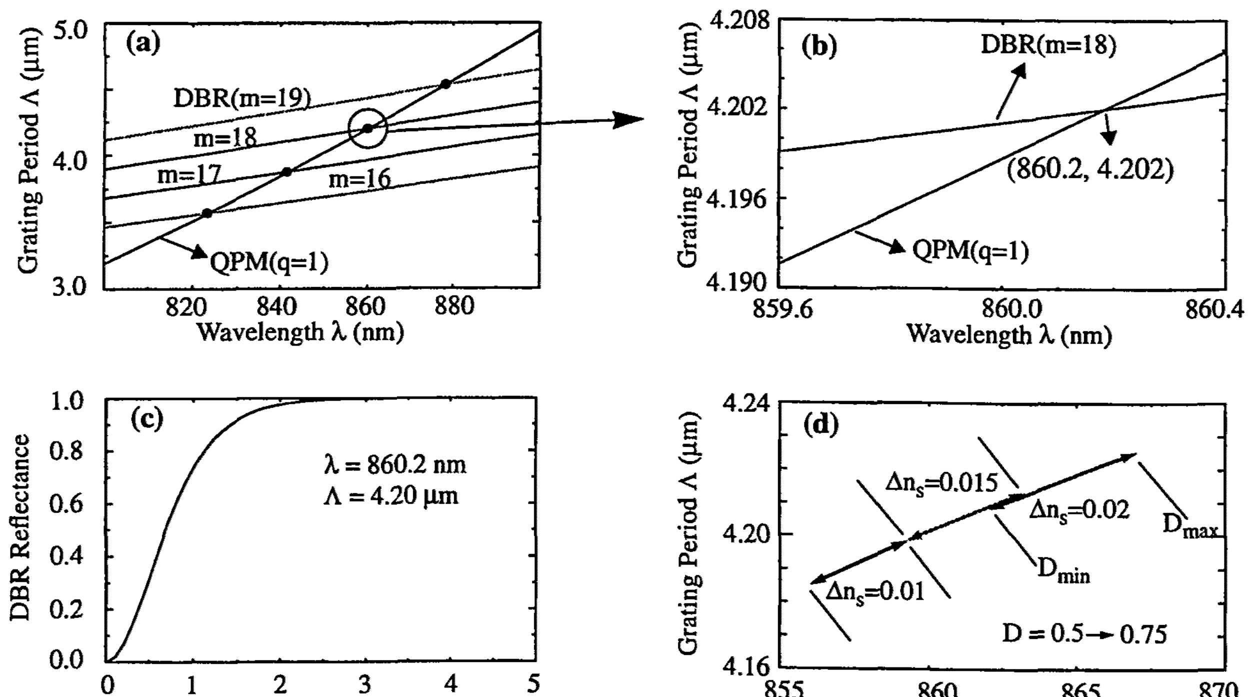

Figure 3 **(a)** Concurrent DBR and QPM grating periods and wavelengths in a KTP PS waveguide; **(b)** Enlarged plot of (a) at a certain cross-over point (q=1, m=18); **(c)** DBR reflectance vs. waveguide length at the concurrent DBR and QPM point of (b); **(d)** Concurrent DBR and QPM grating periods and wavelengths with various Δn_s and D.

IV. SUMMARY AND CONCLUSIONS

We have presented a simplified method to calculate the mode indices in a periodically segmented graded-index channel waveguide for the practical design of a concurrent DBR and QPM SHG device. The method has been used to model a simple device structure in a KTP crystal in which the fabrication tolerance is extremely tight. Similarly, the method can be used to model the superperiod structure which has been proposed for loosening the fabrication tolerance of a concurrent DBR and QPM SHG waveguide in KTP [7]. We intend to use the method to simulate the DBR and QMP SHG properties for designing a more efficient device structure with practically achievable fabrication tolerances.

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