SLAC–PUB–11197
May 2005

DISTRIBUTED BRAGG COUPLER FOR OPTICAL ALL-DIELECTRIC ELECTRON ACCELERATOR*

Z. Zhang, S.G. Tantawi, R.D. Ruth
Stanford Linear Accelerator Center, 2575 Sand Hill Rd., Menlo Park, CA 94025

Abstract

A Bragg waveguide consisting of multiple dielectric layers with alternating index of refraction provides confinement of a synchronous speed-of-light mode with extremely low loss. There are three requirements in designing input coupler for a Bragg electron accelerator: side-coupling, selective mode excitation, and high coupling efficiency. We present a side coupling scheme using a Bragg-grating-assisted input coupler to address these three requirements. Side coupling is achieved by a second order Bragg grating with a period on the order of an optical wavelength. The phase matching condition results in resonance coupling thus providing selective mode excitation capability. We demonstrate a non-uniform distributed grating structure generating an outgoing beam with a Gaussian profile, therefore, increasing the coupling efficiency.

Contributed to 2005 Particle Accelerator Conference
Knoxville, TN, USA
May 16 - May 20, 2005

*Work supported by Department of Energy contract DE–AC02–76SF00515.

DISTRIBUTED BRAGG COUPLER FOR OPTICAL ALL-DIELECTRIC ELECTRON ACCELERATOR*

Z. Zhang†, S. Tantawi, R. Ruth, SLAC, Menlo Park, CA 94025, USA

Abstract

A Bragg waveguide consisting of multiple dielectric layers with alternating index of refraction provides confinement of a synchronous speed-of-light mode with extremely low loss. There are three requirements in designing input coupler for a Bragg electron accelerator: side-coupling, selective mode excitation, and high coupling efficiency. We present a side coupling scheme using a Bragg-grating-assisted input coupler to address these three requirements. Side coupling is achieved by a second order Bragg grating with a period on the order of an optical wavelength. The phase matching condition results in resonance coupling thus providing selective mode excitation capability. We demonstrate a non-uniform distributed grating structure generating an outgoing beam with a Gaussian profile, therefore, increasing the coupling efficiency.

INTRODUCTION

The focus intensity of a high power laser has reached the levels of 10^{22}W/cm^2 [1], which corresponds to an electric field of 10^{14}V/m in vacuum. The wall-plug efficiency of a high power laser system has been improved dramatically due to the rapid development of diode-pumped solid state laser. It therefore becomes increasingly appealing to utilize the intense electric fields available from high power laser pulses to drive charged particle accelerators. Both 1-D [2] and 2-D [3, 4] dielectric photonic crystal structures have been studied and a speed-of-light TM_{01} mode was found to be confined in the vacuum gap in these structures at near-infrared wavelength. The majority of laser power propagates in vacuum resulting in lower absorption loss and less detrimental nonlinear effects.

There are three first-order requirements to design an input coupler for an optical electron accelerator: 1) distributed side coupling; 2) selective mode (accelerating TM mode) excitation; 3) efficient power coupling.

In this paper we propose an out-of-plane input coupler based on second-order Bragg gratings for optical electron accelerators to address the requirements above. We only analyze the input coupler for a planar accelerator structure which confines electromagnetic wave in one-dimension. However, the design principle discussed in the paper can be extended to the case of 2-D confinement.

PLANAR ACCELERATOR STRUCTURE

The theory of periodical layered waveguide structure, or Bragg fiber, was developed by Yeh [5] in 1970s, and the fabrication of Bragg fiber was first demonstrated by Fink *et al.* almost 30-years later [6]. Mizrahi and Schächter extended the application of Bragg waveguide structures to optical electron accelerator [2].

The electromagnetic field in a planar Bragg structure for a TM mode reads:

$$\begin{aligned} E_z^{(i)} &= (A_i e^{-jk_t^{(i)}x} + B_i e^{jk_t^{(i)}x})e^{-j\beta z} \qquad (1)\\ H_y^{(i)} &= -j\frac{n_i^2\omega\varepsilon_0}{k_t^{(i)2}}\frac{\partial E_z^{(i)}}{\partial x} \\ &= \frac{n_i^2\omega\varepsilon_0}{k_t^{(i)}}(-A_i e^{-jk_t^{(i)}x} + B_i e^{jk_t^{(i)}x})e^{-j\beta z} \qquad (2)\end{aligned}$$

where $k_t^{(i)2} = n_i^2 k_0^2 - \beta^2$, β is the propagation constant and n_i the index refraction of the i^{th} layer. z axis is the propagation direction and x axis is normal to the surface of the planar structure. Coefficients A_i and B_i represent the electromagnetic field in a region where dielectric constant is uniform. A represents the amplitude of outgoing wave and B of incoming wave. Considering the boundary conditions that E_z and H_y are continuous at the i_{th} interface between dielectric layer i and $i+1$, a 2×2 matrix can be found which relates A_i, B_i to A_{i+1}, B_{i+1} as:

$$\begin{bmatrix} A \\ B \end{bmatrix}_{i+1} = M_{i+1,x_i}^{-1} M_{i,x_i} \begin{bmatrix} A \\ B \end{bmatrix}_i \qquad (3)$$

where

$$M_{i,x_i} = \begin{bmatrix} e^{-jk_t^{(i)}x_i} & e^{jk_t^{(i)}x_i} \\ -\frac{n_i^2\omega\varepsilon_0}{k_t^{(i)}} e^{-jk_t^{(i)}x_i} & \frac{n_i^2\omega\varepsilon_0}{k_t^{(i)}} e^{jk_t^{(i)}x_i} \end{bmatrix} \qquad (4)$$

Wave confinement can be achieved by choosing the thickness of each layer to minimize the outgoing wave A_i at the interface. Modes confined in a normal vacuum gap Bragg waveguide have phase velocity exceeding the speed-of-light. However, the thickness of the first layer in an accelerator structure is not defined by the quarter wavelength thickness which other layers asymptotically approach; therefore, this layer can be viewed as a defect in the periodical structure. Coupling between the unperturbed propagating mode and the localized defect mode slows down the phase velocity to the speed-of-light in this structure. Figure 1 shows the longitudinal electric field distribution of confined acceleration mode in a waveguide consisting of alternating layers of MgF_2 ($n_L = 1.36$) and TiO_2 ($n_H = 2.2$). The wavelength is at 1064 nm and the vacuum gap is 1μm.

* Work supported by DOE grant No. DE-AC02-76SF00515
† zhiyuz@SLAC.Stanford.EDU

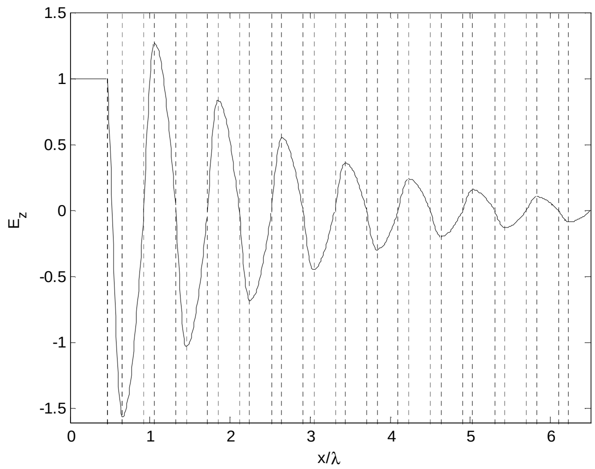

Figure 1: Field distribution (E_z) of a speed-of-light mode in a planar accelerator structure made of TiO_2 and MgF_2. The design wavelength is 1064 nm and the vacuum gap is 1μm.

BRAGG GRATING COUPLER

Dielectric grating has found increasing applications as directional couplers because it can be integrated with waveguides using planar photolithographic techniques thus achieving stable and high efficiency performance.

A grating input/ourput coupler has a period on the order of an optical wavelength and is also called second-order grating. The propagation constants of radiated beam and guided beam are related to the grating period by the phase matching condition:

$$\beta_n \sin\theta_n = \beta + n\frac{2\pi}{\Lambda}, \mathrm{and} \beta = N_{eff}\beta_0 = N_{eff}\frac{2\pi}{\lambda} \quad (5)$$

and the radiated field varies as:

$$\exp[i(\beta_n \sin\theta_n z + i\alpha - \omega t)] \quad (6)$$

where β_n is the propagation constant of the n_{th} order of diffracted beam, Λ is the grating period, N_{eff} is the effective index of refraction of the guided wave and should be calculated numerically, β_0 is unperturbed propagation constant in the waveguide, α is the radiation loss coefficient due to the leakage of the energy into the specific diffracted orders scattered by the grating, and θ_n is the n_{th} order of diffraction angle. Possible radiation beams have real value of θ. The resonance condition at which besides the out-of-plane beam second-order diffraction reflects straight back to the waveguide corresponds $\theta = 0$.

Due to the grating term in Eq(5), grating coupler is able to selectively excite the acceleration mode satisfying the phase matching condition and avoid total internal reflection at the same time. The coupling angle can be tuned in a wide range by grating parameters and therefore the first two requirements of input coupler for optical electron accelerator are naturally satisfied. In this paper, we designed and analyzed grating couplers for the planar accelerator structure using the CAMFR-simulation tool based on eigenmode expansion and propagation technique and perfectly matched layers (PMLs) boundary conditions [7]. Only 1-D gratings was considered, which were etched on the first dielectric layer of planar accelerator structure discussed in the previous section. It is easier for mode expansion technique to calculate output coupling (from waveguide to air); however, the input coupling efficiency can be readily calculated though the reciprocity principle. TM-polarization (E-field normal to the grating groove and on the grating plane) and design wavelength of 1064nm were used throughout this paper.

Figure 2 shows a field plot (E_z) of light coupled from accelerator structure to air through a grating region where a confined synchronized mode couples vertically to a radiated plane wave. Rectangular grating grooves are symmetrically etched on the first dielectric layer on both sides of the vacuum gap. The grating period is 1.08 μm and the groove depth is 50 nm with 50% duty cycle. However, detuning the grating coupler away from the resonance condition is desirable in order to avoid the strong backward diffraction beam.

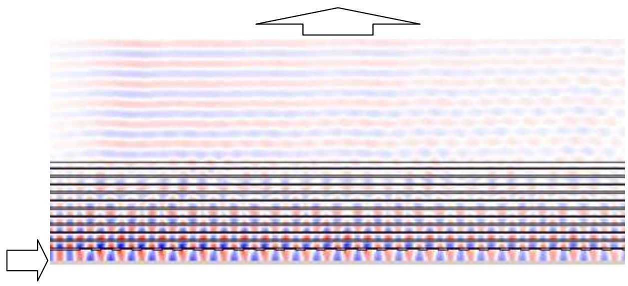

Figure 2: Field plot (E_z) of a grating coupler etched on planar accelerator structure. Shown here is half of the structure cut from the symmetry plane.

NON-UNIFORM GRATING COUPLER

In the previous section we analyzed uniform grating structure where the radiation loss coefficient α shown in Eq.(6) is a constant; therefore, the radiated beam has a characteristic exponential decay profile in the propagation direction. Since laser output is normally a Gaussian profile, the intensity profile mismatch between the input and output beam results in a reduced input coupling efficiency. This effect can be analyzed using the reciprocity principle. The input coupling efficiency is [8]:

$$\eta = P_q \frac{\left(\int g(z)h(z)dz\right)^2}{\int g^2(z)dz \int h^2(z)dz} \quad (7)$$

where $g(z)$ and $h(z)$ represent input and output intensity profile respectively, and P_q is output coupling efficiency. The input coupling efficiency is therefore proportional to a normalized overlap function of input and output intensity profile. Considering the best case scenario of P_q 100%, the maximum input coupling efficiency is 80% for a Gaussian profile input, which is centered at $0.5/\alpha$ with half width of $0.684/\alpha$.

Several techniques have been developed to modulate the radiation loss coefficient along the propagation direction in an attempt to synthesize a desirable intensity profile for planar waveguide input coupler. Since leakage rate is sensitive to the groove depth while the effect on the guiding mode is minimal, side effects of non-uniform gratings such as variations in the coupling angle can be minimized. It is also relatively easier to fabricate groove-depth modulated non-uniform gratings as illustrated in [9]; therefore, we applied this technique to design a non-uniform grating coupler for planar accelerator structure

We define field amplitude of guided wave in the accelerator structure as $A(z)$ and it decays exponentially due to radiation loss characterized by coefficient α:

$$\frac{dA(z)}{dz} = -\alpha A(z) \tag{8}$$

Radiated out-coupled wave is $B(z)$ and it is linearly related to $A(z)$ as
by:

$$B(z) = \beta A(z) \tag{9}$$

Both α and β are constants in a uniform diffraction coupler and both of them are a function of groove depth h. More specifically, α is quadratic and β is linearly related to h in a surface waveguide where fields are evanescent at the grating region; however, this is not the case for a grating coupler on a planar accelerator structures. α and β should be determined numerically by curve fitting. We started with a uniform grating coupler with the period of 1.15 μm and 50% duty cycle, which gives 3.5-degree output coupling at 50 nm groove depth. α and β vary as a function of groove depth and for shallow grooves ($h < 50nm$) they are related to the groove depth h by:

$$\alpha = \mathrm{a}h^2(z) \tag{10}$$
$$\beta = \mathrm{b}h(z) + \mathrm{c}h^2(z) \tag{11}$$

If applying the relations above to Eq (8) and (9), a groove depth profile can be obtained for a given out-coupled wave profile $B(z)$. Figure 3 illustrates the groove depth profile for a Gaussian output beam. The guided field $A(z)$ shown in the same figure is proportional to an error function. Although the radiation loss coefficient is rather small due to the shallow groove depth, the extended grating region (over 5 mm) ensures that nearly 100% power is coupled out. The input coupling efficiency, defined in Eq(7), can approach 100% if using non-uniform grating coupler to match the input beam profile.

CONCLUSION

We have presented an all-dielectric Brag planar electron accelerator structure. Speed-of-light synchronous mode is confined in the structure with very low loss. Side-couplers are essential of distributed pumping the accelerator structure, recycling the residual power, and therefore increasing the overall efficiency. Grating assisted out-of-plane input coupler is proposed to couple laser light to the planar accelerator structure, and to selectively excite the synchronous accelerating mode. The coupling efficiency is optimized by matching the output and input intensity profile with modulated grating depth profile. The planar accelerator structures and gratings can be fabricated using well developed micro-processing technology.

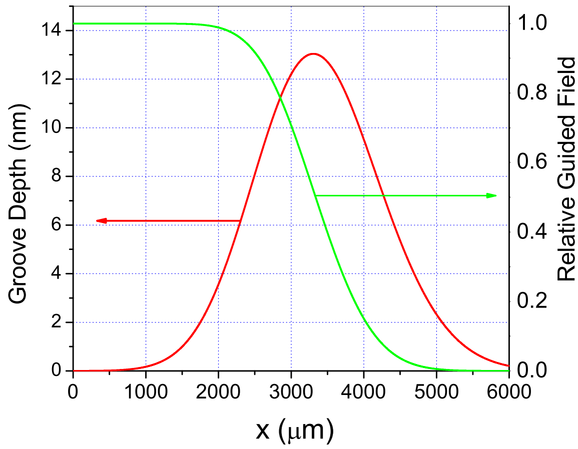

Figure 3: Grating depth profile generating Gaussian output and the relative field strength of guided wave.

REFERENCES

[1] S.W. Bahk *et al.*, “Generation and characterization of the highest laser intensities 10^{22}W/cm^2”, Opt. Lett. **29**, 2837 (2004)

[2] A. Mizrahi and L. Schächter, “Optical Bragg accelerators”, Phy. Rev. E **70**, 0165505 (2004)

[3] X. Lin, “Photonic band gap fiber accelerator”, Phys. Rev. ST Accel. Beams **4**, 051301 (2001)

[4] B.M. Cowan, “Two-dimensional photonic crystal accelerator strucutures”, Phys. Rev. ST Accel. Beams **6**, 101301 (2003)

[5] P. Yeh and A. Yariv, “Theory of Bragg fiber”, J. Opt. Sco. Am **68**, 1196 (1978)

[6] Y. Fink *et al.*, “Guiding optical light in air using an all-dielectric structure”, J. Lightwave Technol. **420**, 650 (1999)

[7] P. Bienstman and R. Baets, “Optical modeling of photonic crystals and VCSEL’s using eigenmode expansion and perfectly matched layers”, Opt. Quantum. Electron. **33**, 327 (2001)

[8] H. Nishihara, M. Haruna and T. Suhara, *Optical integrated circuits* McGraw-Hill, New York, NY, 1989

[9] K.A. Bates *et al.*, “Gaussian beams from variable groove depth grating couplers in planar waveguides”, Appl. Opt. **32**, 2112 (1993)