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International application number:		**PCT/US2018/039541**
International filing date:		**26 June 2018 (26.06.2018)**
Document type:		**Certified copy of priority document**
Document details:	Country/Office:	**US**
	Number:	**62/524,840**
	Filing date:	**26 June 2017 (26.06.2017)**
Date of receipt at the International Bureau:		**14 July 2018 (14.07.2018)**

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a),(b) or (b-*bis*)

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APPLICATION NUMBER: *62/524,840*
FILING DATE: *June 26, 2017*
RELATED PCT APPLICATION NUMBER: *PCT/US18/39541*

THE COUNTRY CODE AND NUMBER OF YOUR PRIORITY APPLICATION, TO BE USED FOR FILING ABROAD UNDER THE PARIS CONVENTION, IS *US62/524,840*

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Doc Code: **TR.PROV**
Document Description: Provisional Cover Sheet (SB16)

PTO/SB/16 (11-08)
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Provisional Application for Patent Cover Sheet

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

Inventor(s)

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All Inventors Must Be Listed – Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Title of Invention	Millimeter Scale Long Grating Coupler With Uniform Spatial Output
Attorney Docket Number (if applicable)	101879.000036/CU17249

Correspondence Address

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Customer Number	23377

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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Yes, the invention was made by an agency of the United States Government. The U.S. Government agency name is:

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HR0011-16-C-0107 awarded by DOD/DARPA

Entity Status
Applicant asserts small entity status under 37 CFR 1.27 or applicant certifies micro entity status under 37 CFR 1.29

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Signature	/Michael P. Dunnam/			Date (YYYY-MM-DD)	2017-06-26
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MILLIMETER SCALE LONG GRATING COUPLER WITH UNIFORM SPATIAL OUTPUT

GOVERNMENT RIGHTS

[0001] This invention was made with Government support under award/contract/grant number HR0011-16-C-0107 awarded by DOD/DARPA. The Government has certain rights in the invention.

TECHNICAL FIELD

[0002] A millimeter scale long grating coupler with a uniform spatial output profile for optical applications is provided by using a platform based on materials such as silicon and silicon nitride (Si_3N_4) and varying the grating output profile to match a desired profile of the output beam.

BACKGROUND

[0003] Long gratings are critical for high resolution Optical Phased Arrays for light detection and ranging (LIDAR) systems among many other applications. However, long gratings are challenging to achieve since the light typically completely leaks out of the gratings after only a few periods due to silicon's high index of refraction compared to the SiO_2 waveguide cladding and grating dimensions. The grating light output is governed by the amount of light interacting with the gratings, known as grating strength. In fiber coupling, strong gratings are favorable for the output beam to match the small diameter of the fiber core. In contrast to fiber coupling, in the case of Optical Phased Arrays, for example, where small beam divergence is required, low strength and long gratings are desirable. Furthermore, the emissions of conventional gratings have an exponential output profile, forcing a trade-off between small beam divergence angle and efficiency (light loss at the end of the gratings and effectively shortening the aperture).

[0004] Previous attempts at fabricating emitters for far-field applications such as light detection and ranging (LIDAR have minimized the perturbation in the silicon waveguide by employing shallow etch depths to reduce the grating coupling strength. However, such a shallow etch is difficult to control accurately. Furthermore, despite the shallow etch, the high index contrast between the substrate and cladding layers inherently results in strong gratings. Fabricating these gratings is very challenging, which could limit their length and increase the beam divergence, ultimately affecting the device resolution. Roelkens et al. in "High efficiency Silicon-on-Insulator grating coupler based on a poly-Silicon overlay," Opt. Express 14, 11622-

11630 (2006) suggested to use a polishing technique with an overlay of poly-Silicon to increase the efficiency of the gratings coupler; however, since the index of the Silicon and poly-Silicon index is comparable, the fabricated gratings strength is high.

[0005] More recently, Raval et al. disclosed in "Unidirectional waveguide grating antennas with uniform emission for optical phased arrays," Optics Letters, Posted June 6, 2017, a design including two silicon nitride layers where the perturbation strength along the antenna is apodized at the sides of the waveguide to achieve uniform emission on a millimeter scale. The required perturbation strength profile is tailored to achieve a uniform output profile. The grating strength is tailored by changing the amount of indent along the waveguide. However, such a device has a complicated fabrication process. Furthermore, due to the small index contrast of this platform, the ability to steer an output beam by controlling the light's wavelength is limited.

[0006] A further improved grating coupler design is desired that provides a uniform spatial output profile over a millimeter scale long grating with robust and straightforward fabrication process. The device described herein addresses these and other needs in the art.

SUMMARY

[0007] To design a millimeter scale weak grating coupler that could function as an antenna, for example, and provides a near uniform output profile, the inventors recognized that the total light emission is related to the corrugated structure of the gratings and the ability of the gratings to emit light (its strength) and amount of light in the waveguide. In particular, if the gratings strength is constant along the waveguide, it means the total emission will have a nonlinear (exponential) profile since some of the light is emitted along the gratings and the intensity of light in the waveguide is reduced as the grating gets further from the light source. Thus, to obtain a uniform output profile, the gratings are engineered so that they are less strong in the beginning of the grating structure closer to the light source and the strength increases as the distance from the light source is increased. That way the overall emission due to the grating strength and light intensity in a waveguide can be made uniform along an entire millimeter structure.

[0008] In exemplary embodiments, this engineered structure is achieved by changing the length of the Si_3N_4 bars above the Silicon waveguide. A uniform grating output is achieved by varying the duty cycle of the Si_3N_4 bars (length a) as a portion of the period length (Λ) of each constant grating period along the entire length of the gratings. Using the Si_3N_4 as a low index material overlay, the index contrast between the grating layer and the surrounding cladding are simultaneously reduced while the grating perturbation is also moved further away from the mode that travels in the silicon waveguide thus achieving low grating strength.

[0009] In further exemplary embodiments, the grating coupler is formed by creating bars of Si_3N_4 of length a disposed periodically at a period length Λ above a silicon waveguide whereby a duty cycle of a/Λ is varied along a top of the silicon waveguide so as to provide a uniform grating output. Typically, the duty cycle decreases along the silicon waveguide as the grating strength decreases. The techniques may be used to form gratings of arbitrary lengths.

[0010] In other exemplary embodiments, the grating coupler is formed by depositing on a Silicon On Insulator (SOI) wafer a thin (*e.g.*, 3-5 nm) stop layer of Al_2O_3, depositing an Si_3N_4 grating layer on the stop layer, patterning desired gratings, and etching the grating layer to the stop layer in accordance with a flat-top function whereby bars of Si_3N_4 of length a are disposed periodically at a period Λ above the wafer whereby a duty cycle of a/Λ decreases along the wafer moving away from a light source whereby a uniform grating output is achieved. A waveguide is patterned and etched from the wafer whereby the duty cycle of a/Λ decreases along the waveguide moving away from the light source. SiO_2 may also be deposited on the grating coupler to provide cladding. In the exemplary embodiments, duty cycles of the gratings are analytically mapped to a flat-top required strength set forth by the flat-top function so as to produce a profile of duty cycles per period for an entire length of the gratings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The above and other objects and advantages of the invention will be apparent to those skilled in the art based on the following detailed description in conjunction with the appended figures, of which:

[0012] Fig. 1(a) shows a cross section of a device in accordance with an exemplary embodiment.

[0013] Fig. 1(b) shows a tilted Scanning Electron Microscopy picture of the gratings overlaying the silicon waveguide.

[0014] Fig. 2 illustrates a grating having a constant period (Λ) but a varied duty cycle (a/Λ) that has a relatively high value at the beginning of the grating near the light source and a relatively low value at the end of the grating away from the light source.

[0015] Fig. 3 shows the very small beam divergence of 0.086° measured from a 1 mm uniform output grating developed using the techniques described herein as well as angle tuning measured to be 16.6° over 100 nm of wavelength tuning (extrapolated).

[0016] Fig. 4(a) illustrates the grating strength for several fabricated duty cycles for devices with a 120 nm Si_3N_4 overlay grating layer.

[0017] Fig. 4(b) illustrates a comparison of the spatial distribution of light from a Si_3N_4 grating overlay with constant duty cycle (50%) and from the designed Si_3N_4 grating with custom duty cycle.

[0018] Fig. 5 illustrates the grating strength converted to duty cycle.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0019] An exemplary embodiment of a method and device for obtaining a grating coupler with a uniform output profile is described below with respect to Figs. 1-5. Those skilled in the art will appreciate that the steps and devices described are for exemplary purposes only and are not limited to the specific processes or devices described.

Overview

[0020] A long grating with uniform output profile is provided by using a platform based on Silicon and Si_3N_4 and uniform grating output is achieved by varying the duty cycle along the length of the gratings. Using the Si_3N_4 as a low index material overlay, the index contrast between the grating layer and the surrounding cladding are simultaneously reduced while also moving the grating perturbation further away from the mode that travels in the Silicon waveguide thus achieving low grating strength. The overlay also increases the fabrication robustness since it is straightforward to deposit such a layer uniformly and the grating strength is less sensitive to the layer thickness compared to conventional etching into the Silicon. The uniform grating output is engineered by first creating a normalized flat-top output. Then, the grating strength required for a flat-top function is found using the relationship:

$$2\alpha(z) = \frac{F^2(z)}{1 - \int_{zo}^{z} F^2(z)dz}$$

Equation (1)

where α is the grating strength and F is the flat-top function, or any function for the desired emission. Finally, for each period, the grating strength is converted to duty cycle as reflected in Fig. 5. This process results in roughly varying the duty cycle from high at the beginning of the grating to low at the end, which in turn varies the output from weak to strong, flattening the output as the optical power in the waveguide decays along its length.

Device Structure

[0021] As described herein, a low strength grating which is robust to fabrication variation can be achieved using a platform based on both silicon and Si_3N_4. Fig. 1(a) shows a cross section of a device in accordance with an exemplary embodiment. As shown the Al_2O_3 stop layer and Si_3N_4 grating layer are provided on top of the Silicon on Insulator (SOI) wafer. Fig. 1(b) shows a tilted Scanning Electron Microscopy picture of the gratings overlaying the silicon waveguide. In exemplary embodiments, a uniform grating output can be achieved by varying the duty cycle a/Λ along the length of the gratings. Using the Si_3N_4 as a low index material overlay, the index contrast between the grating layer and the surrounding cladding are simultaneously reduced while the grating perturbation is also moved further away from the mode that travels in the Silicon waveguide thus achieving low grating strength. The overlay also increases the fabrication robustness since it is straightforward to deposit such a layer uniformly and the grating strength is less sensitive to the layer thickness compared to conventional etching into the Silicon. A thin stop layer protects the silicon during the Si_3N_4 etch, since etching the silicon will increase the grating strength. A uniform grating output is engineered by first creating a normalized flat-top output. Then, similar to the process described by Waldhausl et al. in "Efficient Coupling into Polymer Waveguides by Gratings," Appl. Opt. 36, 9383 (1997), the strength per period corresponding to the flat-top function is found. Finally, for each period, the grating strength is converted to duty cycle. As illustrated in Fig. 2, this process results in roughly varying the duty cycle from high at the beginning of the grating to low at the end, which in turn varies the output from weak to strong, flattening the output profile as the optical power in the waveguide decays along its length.

[0022] Fig. 3 shows the minimal beam divergence of 0.086° measured from a 1 mm uniform output grating developed using the techniques described herein. As also shown in Fig. 3, angle tuning was also measured (between 1545 nm - 1550 nm) to be 16.6° over 100 nm of laser tuning.

Device Fabrication

[0023] A multilayer deposition process is used to form the silicon nitride gratings and underlying waveguides. Starting with a Silicon On Insulator (SOI) wafer with a 250 nm silicon device layer and a 3 µm buried oxide layer, a very thin (3-5 nm) stop layer of Al_2O_3 is deposited followed by another deposition of 120 nm Si_3N_4 grating layer. A thin stop layer protects the silicon during the Si_3N_4 etch, since etching the silicon will increase the grating strength. After using electron-beam lithography (Elionix) to pattern the gratings, the Si_3N_4 film is etched to the Al_2O_3 stop layer (see Fig. 1). The waveguides are then patterned and etched and the process finishes with cladding the wafer by depositing SiO_2 on the devices. Light is coupled to the waveguides using edge couplers and lensed fibers at 1550 nm. The grating output is imaged using an IR camera, which is used to measure the light output from the grating.

[0024] The inventors have experimentally demonstrated low grating strength of 3.5 [1/mm] at 50% duty cycle with good agreement to simulations, which is a much lower grating strength than the 150 [1/mm] grating strength of a simulated typical silicon shallow etch gratings (220 nm Si, 2 μm box, 25 nm etch, period 0.6 μm). The grating strength for several fabricated duty cycles is plotted in Fig. 4(a) for devices with a 120 nm Si_3N_4 overlay grating layer. As illustrated, the 50% duty cycle is the strongest and the gratings strength decreases thereafter, as expected. The higher strength of the experimental gratings compared to the simulation results could be due to the thin stop layer. The Al_2O_3 stop layer was only 3 nm thick, and the Si_3N_4 etch penetrated it slightly and created a shallow grating of 2-3 nm deep in the silicon waveguide layer. This increased the overall grating strength.

[0025] By varying the duty cycles a/Λ along the gratings length to match a flat-top function, it is possible to achieve a much more uniform near-field output than that of a constant duty cycle over a grating having a length of one millimeter or less. The grating strength is calculated for several gratings with different duty cycles by fitting their near-field output to an exponent. Then, the grating strength required for a flat-top function is found using Equation (1) above, where α is the grating strength and F is the flat-top function. In the last step, duty cycles of the gratings are analytically mapped to the flat-top required strength, producing a profile of duty cycles per period for the entire gratings length. Fig. 4(b) shows a comparison of the spatial distribution of light from a Si_3N_4 grating overlay with constant duty cycle (50%) and from the designed Si_3N_4 grating with custom duty cycle. As illustrated, the designed grating (Si_3N_4 custom duty cycle) has an almost uniform intensity as a function of length along the grating compared to the diminished intensity as a function of length along the grating shown for the constant duty cycle grating (SiN 0.5 constant duty cycle).

[0026] The techniques disclosed herein demonstrate control over the strength of the grating and the near-field output profile of the beam. A Si_3N_4 overlay is used on the SOI substrate to fabricate a near-uniform grating output over 1 mm or less with low grating strength measured over various duty cycles. By engineering the duty cycle of the gratings, it is shown that using different grating strengths along the grating length increases the gratings near-field output uniformity. Those skilled in the art will appreciate that the techniques described herein provide a path for integrating gratings in Optical Phased Arrays with very narrow beam divergence and high resolution.

What is Claimed:

1. A millimeter scale weak grating coupler comprising a silicon waveguide having bars of Si_3N_4 of length a disposed periodically at a period Λ above the silicon waveguide whereby a duty cycle of a/Λ is varied along a top of the silicon waveguide whereby a uniform grating output is achieved.

2. The grating coupler as in claim 1, wherein the duty cycle decreases along the silicon waveguide as the grating strength decreases.

3. A method of forming a grating coupler that provides a uniform grating output, comprising:

depositing on a Silicon On Insulator (SOI) wafer a thin stop layer of Al_2O_3;
depositing an Si_3N_4 grating layer on said stop layer;
patterning desired gratings; and
etching the grating layer stopping on the Al_2O_3 creating the gratings as per the flat-top function whereby the bars of Si_3N_4 of length a are disposed periodically at a period Λ above the wafer whereby a duty cycle of a/Λ decreases along the wafer moving away from a light source whereby a uniform grating output is achieved.

4. The method of claim 3, further comprising patterning and etching a waveguide from said wafer whereby said duty cycle of a/Λ decreases along the waveguide moving away from the light source.

5. The method of claim 4, further comprising depositing SiO_2 on the grating coupler to provide cladding.

6. The method of claim 3, further comprising analytically mapping duty cycles of the gratings to a flat-top required strength set forth by said flat-top function so as to produce a profile of duty cycles per period for an entire length of the gratings.

ABSTRACT

A long and uniform-output grating coupler is formed by depositing bars of Si_3N_4 of length (a) disposed periodically at a period ^ above a silicon waveguide whereby a duty cycle of a/^ is varied along a top of the silicon waveguide whereby a uniform emission profile output is achieved. Typically, the duty cycle decreases along the silicon waveguide as the grating strength decreases. The techniques may be used to form grating couplers of arbitrary lengths.

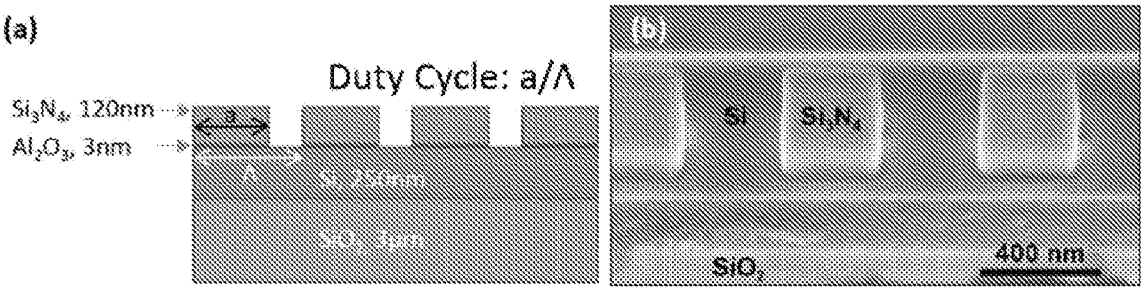

FIGURE 1

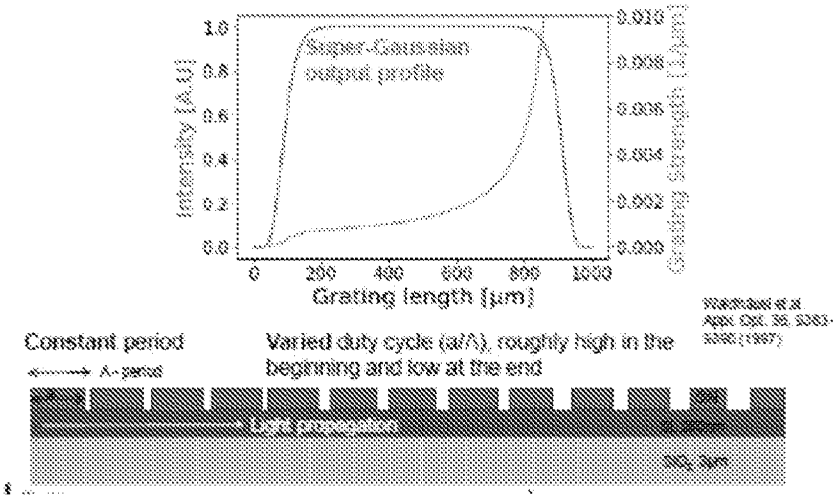

FIGURE 2

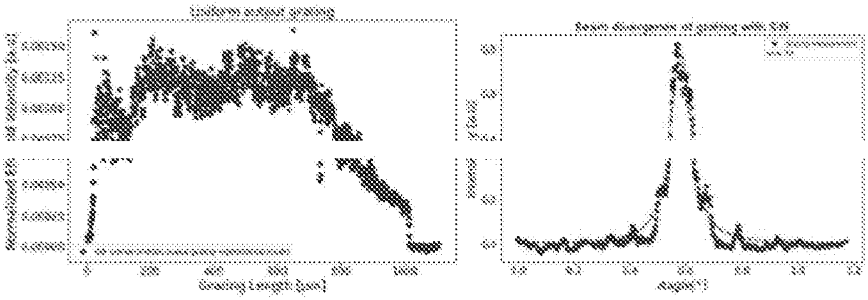

FIGURE 3

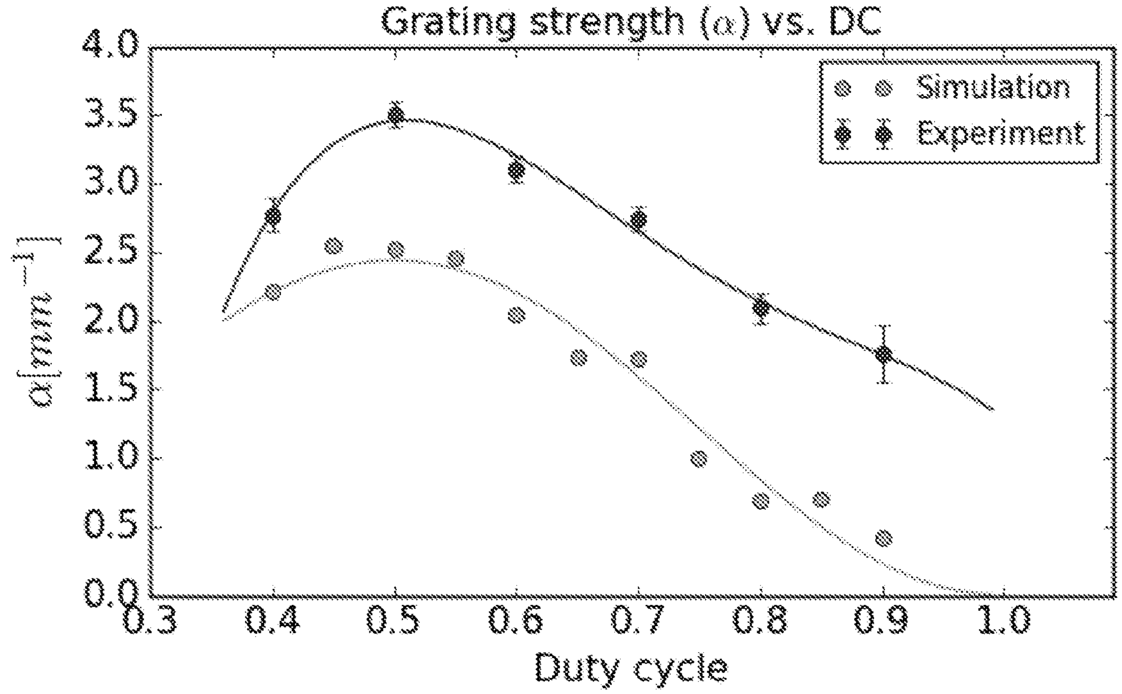

FIGURE 4(A)

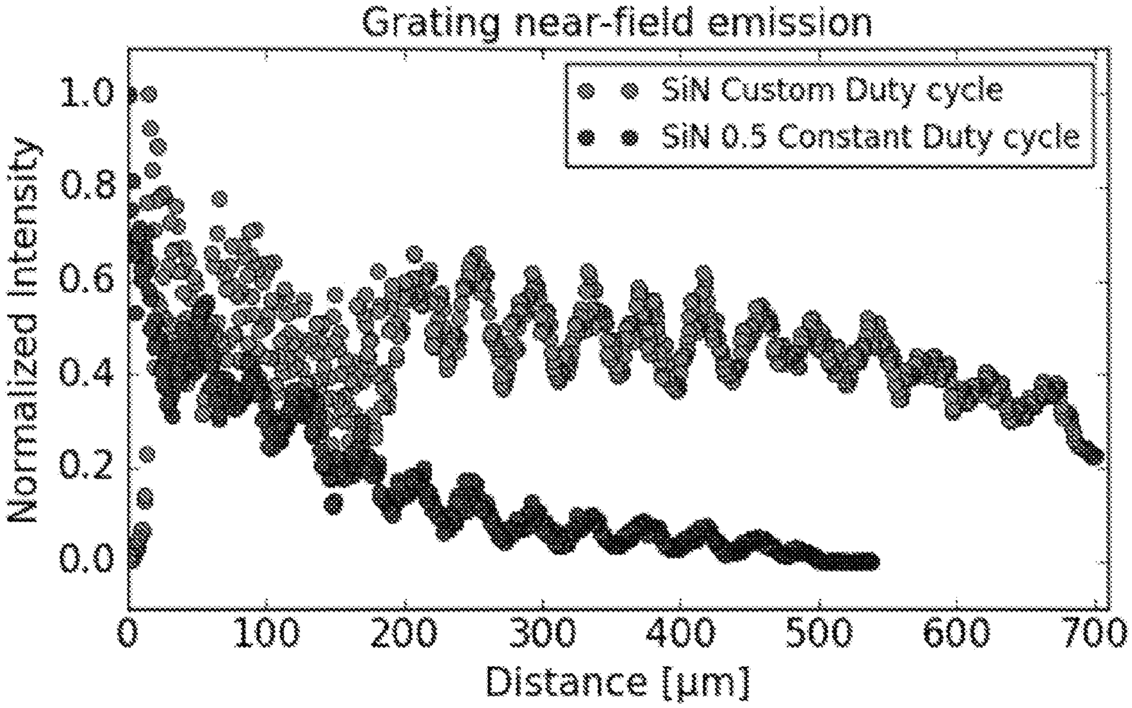

FIGURE 4(B)

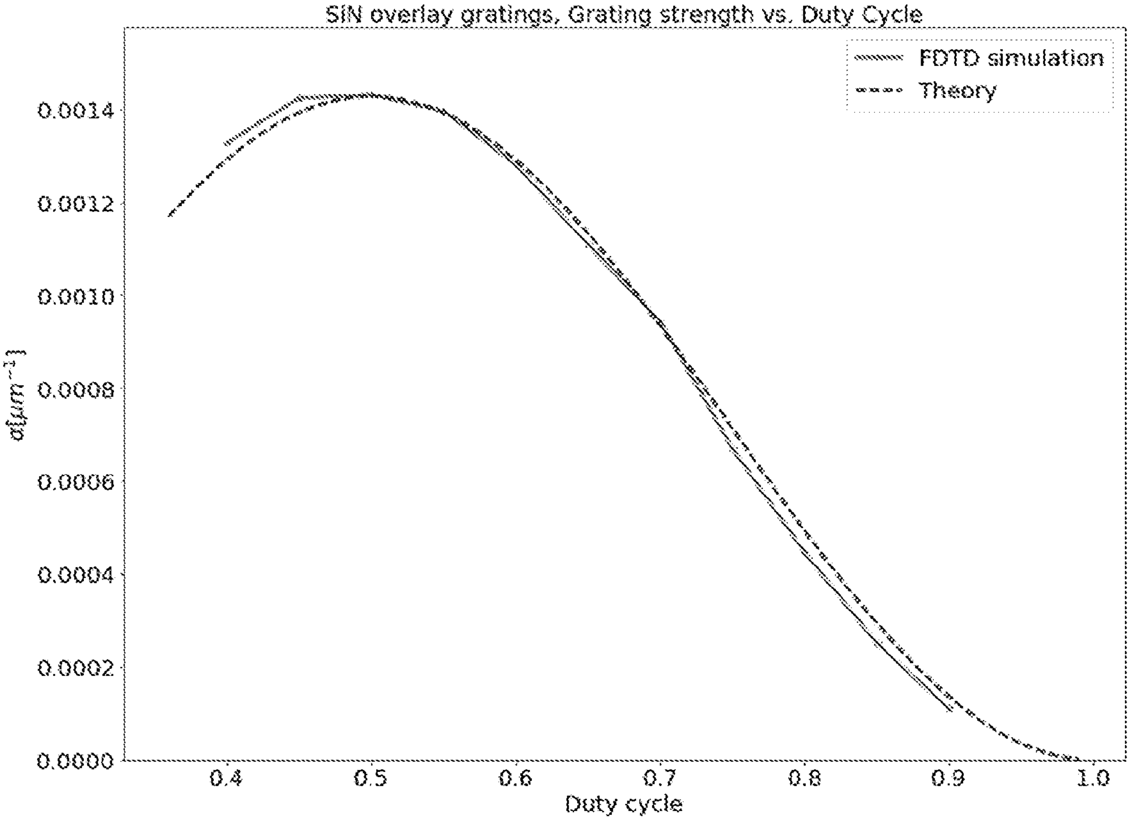
SiN overlay gratings, Grating strength vs. Duty Cycle
FDTD simulation
Theory
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
$\alpha[\mu m^{-1}]$
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Duty cycle

FIGURE 5

Electronic Acknowledgement Receipt

EFS ID:	29608423
Application Number:	62524840
International Application Number:	
Confirmation Number:	4857
Title of Invention:	Millimeter Scale Long Grating Coupler With Uniform Spatial Output
First Named Inventor/Applicant Name:	Michal Lipson
Customer Number:	23377
Filer:	Michael Paul Dunnam/Denise Marvel
Filer Authorized By:	Michael Paul Dunnam
Attorney Docket Number:	101879.000036/CU17249
Receipt Date:	26-JUN-2017
Filing Date:	
Time Stamp:	15:49:00
Application Type:	Provisional

Payment information:

Submitted with Payment	yes
Payment Type	DA
Payment was successfully received in RAM	$130
RAM confirmation Number	062717INTEFSW00002702233050
Deposit Account	233050
Authorized User	Denise Marvel

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2		101879_000036_Application.PDF	169963 6d1b056668524b9a249983c28edb6a66f16fc14e	yes	8

Multipart Description/PDF files in .zip description

Document Description	Start	End
Specification	1	6
Claims	7	7
Abstract	8	8

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3	Drawings-only black and white line drawings	101879_000036_Figures.PDF	677723 45da9643727ccfd5094119074cc6a9aecae0a3bf	no	3

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4	Fee Worksheet (SB06)	fee-info.pdf	30248 de0c5f17916b08ad2211bd2722f354592ceb3a99	no	2

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