

Analysis of the Modal Behavior of an Antiguided Diode Laser Array with Talbot Filter

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Abstract—An analysis of the filtering of the array modes in a resonant optical waveguide (ROW) array of antiguides by a diffractive spatial filter, a so-called Talbot filter, is presented. A dispersion relation is derived for the array modes enabling the calculation of the field distribution. The filtering is analyzed by calculating the field propagation of each array mode in an array structure with a Talbot filter by means of the beam-propagation method. It is shown that in the presented array structure only the resonant in-phase mode will lase.

I. INTRODUCTION

APPLICATIONS of diode laser arrays in optical computing and free-space communication require high powers in stable, diffraction-limited beams [1]. Single in-phase array-mode operation is a requisite since array operation of a mixture of the in-phase mode and other array modes will give rise to a nondiffraction limited output. Therefore, the other modes have to be suppressed.

Recently, an ROW array of antiguides with a monolithically integrated Talbot filter to suppress the out-of-phase mode has been reported [2]–[4]. The effect of the Talbot filter on the out-of-phase, the in-phase mode, and its adjacent modes has been analyzed by calculating a field overlap integral [5]. Up to now, however, to our knowledge, no analysis of the discrimination of the Talbot filter against the array modes has been made by actually calculating the field propagation of each array mode in a structure with a monolithically integrated Talbot filter.

II. THEORY

In order to find the array modes in the array of L antiguides (L is odd in our case) the problem has been simplified to a two-dimensional one by representing the array by a multilayered structure of N layers ($N = 2L + 1$) with an alternating complex refractive index $\bar{n}_1, \bar{n}_0, \bar{n}_1, \dots, \bar{n}_0, \bar{n}_1$ ($\text{Re}\{\bar{n}_0\} < \text{Re}\{\bar{n}_1\}$) [2]. Fig. 1 displays the multilayered structure in which the indexes \bar{n}_0 and \bar{n}_1

are the effective indexes corresponding with the antiguided core and cladding, respectively. The antiguided core has width d and the cladding, the so-called interelement region, has width s .

An ROW array of antiguides has a resonant in-phase array mode which is characterized by strong interelement coupling resulting in a uniform intensity profile. The interelement spacing needed for a resonant operation of the in-phase mode, TE or TM polarized, can be found easily by using the following equation [2]:

$$s_{\text{res}} \approx \frac{L\lambda}{2\sqrt{\text{Re}\{n_1\}^2 - \text{Re}\{n_0\}^2 + (\lambda/2d)^2}},$$

$$L = 1, 3, 5, \dots \quad (1)$$

in which λ is the wavelength of the laser array. Single, resonant in-phase array-mode operation will not only result in a diffraction-limited but also in a strong coherent output.

A. The Dispersion Relation

Field equations have been derived for both TM- and TE-polarized modes in the multilayered structure shown in Fig. 1. The solution of the magnetic (TM) and the electric (TE) fields in the y direction is denoted by the following set of equations in which the origin of our coordinate system has been chosen at the center of the array (the term $\exp[j(\omega t - \beta z)]$ has been omitted for simplicity):

$$A_{-N} = B_{-N} \exp[jh_N(x + t_n)] \quad x < -t_n \quad (2a)$$

$$\vdots \quad \vdots \quad \vdots$$

$$A_{-i} = B_{-i} \cos[h_i(x + t_i) - \phi_{-(i-1)}] \quad -t_{i+1} < x < -t_i \quad (2b)$$

$$\vdots \quad \vdots \quad \vdots$$

$$A_0 = B_0 \cos[h_0x - \phi_0] \quad t_{-1} < x < t_1 \quad (2c)$$

$$\vdots \quad \vdots \quad \vdots$$

$$A_i = B_i \cos[h_i(x - t_i) - \phi_{(i-1)}] \quad t_i < x < t_{i+1} \quad (2d)$$

$$\vdots \quad \vdots \quad \vdots$$

$$A_N = B_N \exp[-jh_N(x - t_n) - \phi_{(i-1)}] \quad t_N < x \quad (2e)$$

Manuscript received July 16, 1990; revised November 13, 1990.
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 IEEE Log Number 9042362.

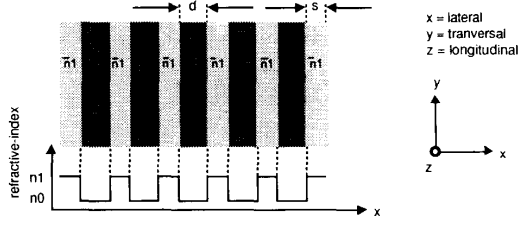


Fig. 1. Multilayered structure with alternating layers of refractive index \bar{n}_0 and \bar{n}_1 . The antiguide core width and the interelement spacing are denoted by d and s , respectively. (Only five antiguides shown.)

in which

$$A_i = E_y(x) \text{ for TE polarized modes} \quad (3a)$$

$$A_i = H_y(x) \text{ for TM polarized modes.} \quad (3b)$$

The constants B_i follow from the continuity of A_i at the interfaces. The lateral propagation vector h_i is defined as

$$h_i = k_0 \sqrt{\bar{n}_x^2 - \bar{n}_{\text{eff}}^2}, \quad x \in \{0, 1\} \quad (4)$$

in which k_0 equals $2\pi/\lambda_0$, λ_0 being the free-space wavelength. The complex refractive indexes \bar{n}_0 and \bar{n}_1 are written as

$$\bar{n}_x = n_x + j \frac{g_x}{2k_0}, \quad x \in \{0, 1\} \quad (5)$$

where $g_x > 0$ represents gain and $g_x < 0$ loss. The effective index \bar{n}_{eff} of the array mode(s) is defined as

$$\bar{n}_{\text{eff}} = n_{\text{eff}} + j \frac{g_{\text{eff}}}{2k_0} \quad (6)$$

in which g_{eff} represents the modal gain. The constants t_i are defined as

$$t_i = \frac{(i-1)}{2}(s+d) + \frac{d}{2} \quad i = \text{odd}, 1 \leq |i| \leq N$$

$$t_i = \frac{i}{2}(s+d) - \frac{d}{2}$$

$$i = \text{even}, 2 \leq |i| \leq (N-1). \quad (7b)$$

The phase terms ϕ_i , which follow from the continuity of the H_z (E_y) components for TE (TM) modes at the interfaces, are written as

$$\phi_{-(N-1)} = \arctan \left\{ -j \frac{h_N}{h_{N-1}} \left[\frac{\bar{n}_{N-1}}{\bar{n}_N} \right]^p \right\} - h_{N-1}d \quad (8a)$$

⋮

$$\phi_{-i} = \arctan \left\{ \tan [\phi_{-(i+1)}] \frac{h_{i+1}}{h_i} \left[\frac{\bar{n}_i}{\bar{n}_{i+1}} \right]^p \right\} - h_i l_i \quad (8b)$$

⋮

$$\phi_0 = \frac{m\pi}{2} \quad (8c)$$

⋮
⋮
⋮

$$\phi_i = -\arctan \left\{ \tan [-\phi_{(i+1)}] \frac{h_{i+1}}{h_i} \left[\frac{\bar{n}_i}{\bar{n}_{i+1}} \right]^p \right\} + h_i l_i \quad (8d)$$

⋮
⋮

$$\phi_{N-1} = -\arctan \left\{ j \frac{h_N}{h_{N-1}} \left[\frac{\bar{n}_{N-1}}{\bar{n}_N} \right]^p \right\} + h_{N-1}d \quad (8e)$$

in which

$$p = 0 \text{ for TE polarization} \quad (9a)$$

$$p = 2 \text{ for TM polarization} \quad (9b)$$

and where

$$l_i = d \text{ if } i \text{ is even} \quad (10a)$$

$$l_i = s \text{ if } i \text{ is odd.} \quad (10b)$$

Based on the continuity of the fields a dispersion relation for TE and TM polarization can be derived from (2)-(10)

$$\bar{n}_0^2 - \bar{n}_{\text{eff}}^2 = \left[\frac{1}{dk_0} \right]^2 \left\{ 2 \arctan \left[\tan(-\phi_1) \left(\frac{\bar{n}_0}{\bar{n}_1} \right)^p \right. \right.$$

$$\left. \left. \sqrt{\frac{\bar{n}_1^2 - \bar{n}_{\text{eff}}^2}{\bar{n}_0^2 - \bar{n}_{\text{eff}}^2}} \right] + m\pi \right\}^2. \quad (11)$$

By varying the integer m , which equals 0, 1 or 2, all the array modes can be found. For an array of L antiguides more than L modes exist, however, the first L modes have a much higher modal gain than the remaining ones and those will only be considered here.

B. The Talbot Filter

Wilcox *et al.* [6] showed that a set of in-phase Gaussian curves, representing the in-phase mode, will shift laterally by $(d+s)/2$ after having propagated a half-Talbot distance through a homogeneous medium. This half-Talbot distance $Z_T/2$ is defined as

$$Z_T/2 = \frac{\Lambda^2 n}{\lambda} \quad (12)$$

in which n is the real part of the refractive index of the homogeneous medium in the Talbot filter, and Λ being the center-to-center array element spacing $(s+d)$. It has also been shown [6] that a set of out-of-phase Gaussian curves, representing the out-of-phase mode will mirror at half-Talbot distance. Mawst *et al.* [3] used an array structure with two noncolinear sets of antiguides separated by a half-Talbot distance, as depicted in Fig. 2, to suppress the out-of-phase mode. (The second set of antiguides has an extra element since the Talbot filtering introduces an extra "Gaussian" for the in-phase mode.) At the end of the Talbot filter a major part of the intensity of this mode is situated in the interelement regions, characterized by high losses, resulting in the suppression of the out-of-

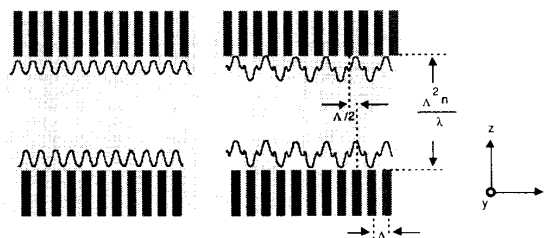


Fig. 2. Schematic representation of two noncolinear sets of antiguides separated by the half-Talbot distance; field amplitudes of the in- and out-of-phase mode.

TABLE I
REAL PARTS OF THE EFFECTIVE INDEXES AND MODAL GAINS OF THE ELEVEN ARRAY MODES, TE
AND TM POLARIZED

Array Mode Number	Dispersion Relation		Slab-Solving Program			
	TM Polarization		TM Polarization		TE Polarization	
	n_{eff}	g_{eff} [cm^{-1}]	n_{eff}	g_{eff} [cm^{-1}]	n_{eff}	g_{eff} [cm^{-1}]
1	3.412 000	58.594	3.412 000	58.533	3.412 000	59.033
2	3.412 412	31.562	3.412 411	31.486	3.412 408	31.270
3	3.412 779	33.900	3.412 781	33.887	3.412 774	33.608
4	3.413 106	36.238	3.413 103	36.214	3.413 100	36.092
5	3.413 397	38.576	3.413 399	38.528	3.413 389	38.284
6	3.413 650	40.622	3.413 647	40.541	3.413 641	40.329
7	3.413 867	42.375	3.413 863	42.420	3.413 857	42.083
8	3.414 044	43.982	3.414 043	43.900	3.414 033	43.544
9	3.414 183	45.151	3.414 183	45.086	3.414 172	44.713
10	3.414 283	46.028	3.414 283	46.026	3.414 271	45.590
11	3.414 343	46.612	3.414 341	46.494	3.414 331	46.174

phase mode. However, an overall analysis of the effect of the Talbot filter on all the array modes has not yet been reported.

III. COMPUTATIONAL RESULTS

An array of eleven antiguides, emitting at 860 nm, has been analyzed. The refractive indexes of the antiguides (core width $3 \mu\text{m}$) n_0 , and of the interelement regions n_1 , have been taken as 3.415 and 3.465, respectively. Furthermore, the gain g_0 in the antiguides was set at 75 cm^{-1} , while the gain g_1 in the interelement regions was chosen as -75 cm^{-1} , representing losses. The interelement spacing needed for a resonant operation of the in-phase mode can be found using (1) (L has been taken as 3): $s_{\text{res}} = 2.14 \mu\text{m}$. The length of both sets of antiguides (Fig. 2) was taken as $50 \mu\text{m}$. The sets were separated by a uniform area with a refractive index equal to n_1 and with losses of 15 cm^{-1} . Using (12) we find a half-Talbot distance of $106.4 \mu\text{m}$.

A. Array-Mode Calculation

The effective indexes of the eleven array modes were calculated by solving the dispersion relation (11) using a standard mathematical function [9] based on Secant's method. Table I shows the real part n_{eff} of the effective

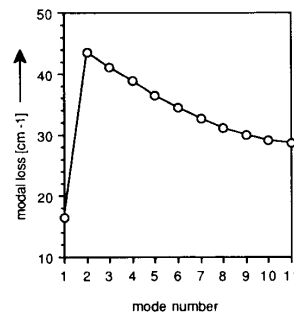


Fig. 3. Modal losses ($g_{\text{eff}} - g_0$) of the eleven array modes (TM polarized) in an ROW array of antiguides.

indexes and the modal gain of the TM-polarized array modes, which are within a small interval of n_{eff} . The solutions found by means of the dispersion relation were in good agreement with those found by an ordinary slab-solving program using a 2D-Newton-Raphson iteration in the complex β -plane starting at the values found by the dispersion relation, as can be inferred from Table I. It also shows that the effective indexes for TE- and TM-polarized modes are in close proximity. The intensity profiles of modes 1, 2, and 11, TM polarized, are depicted in Figs.

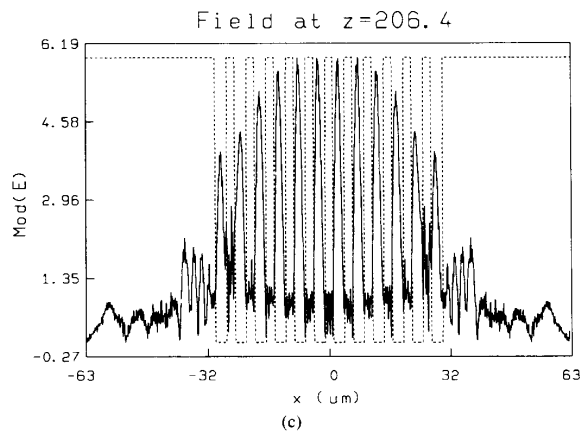
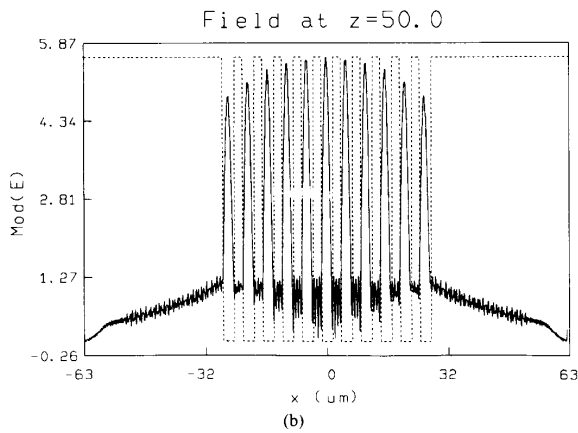
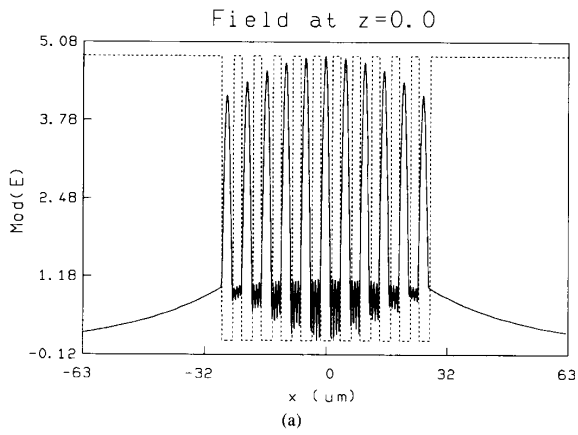


Fig. 4. Intensity profiles of (a) mode 1 at $z = 0 \mu\text{m}$, (b) mode 1 at $z = 50 \mu\text{m}$, and (c) mode 1 at $z = 206.4 \mu\text{m}$. (The dashed lines represent the real refractive-mode profile.)

4(a), 5(a), and 6(a), respectively. The in-phase mode, mode 1, operates close to resonance since its intensity profile is nearly uniform.

Fig. 3 depicts the modal loss ($g_{\text{eff}} - g_0$) of the eleven array modes (TM polarized). It can be inferred from this

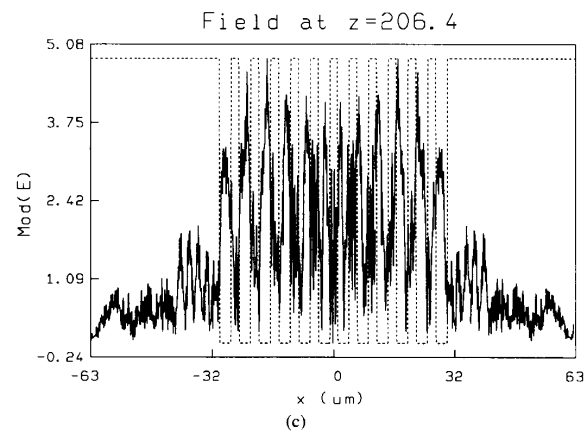
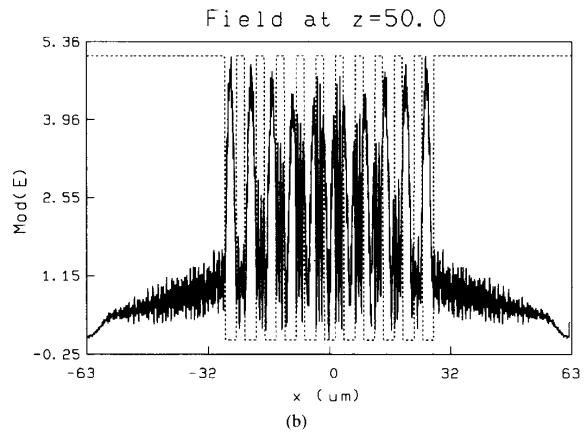
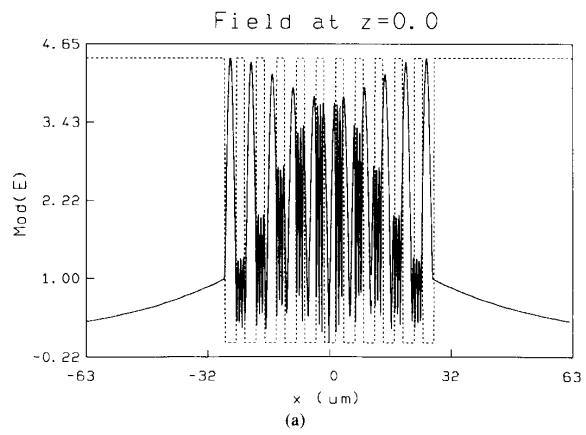


Fig. 5. Intensity profiles of (a) mode 2 at $z = 0 \mu\text{m}$, (b) mode 2 at $z = 50 \mu\text{m}$, and (c) mode 2 at $z = 206.4 \mu\text{m}$. (The dashed lines represent the real refractive-index profile.)

figure and from Table I that the in-phase mode, mode 1, is favorite to lase since it has the highest modal gain. The other array modes can emerge with increasing drive level, resulting in a nondiffraction limited output. Therefore, these modes have to be suppressed.

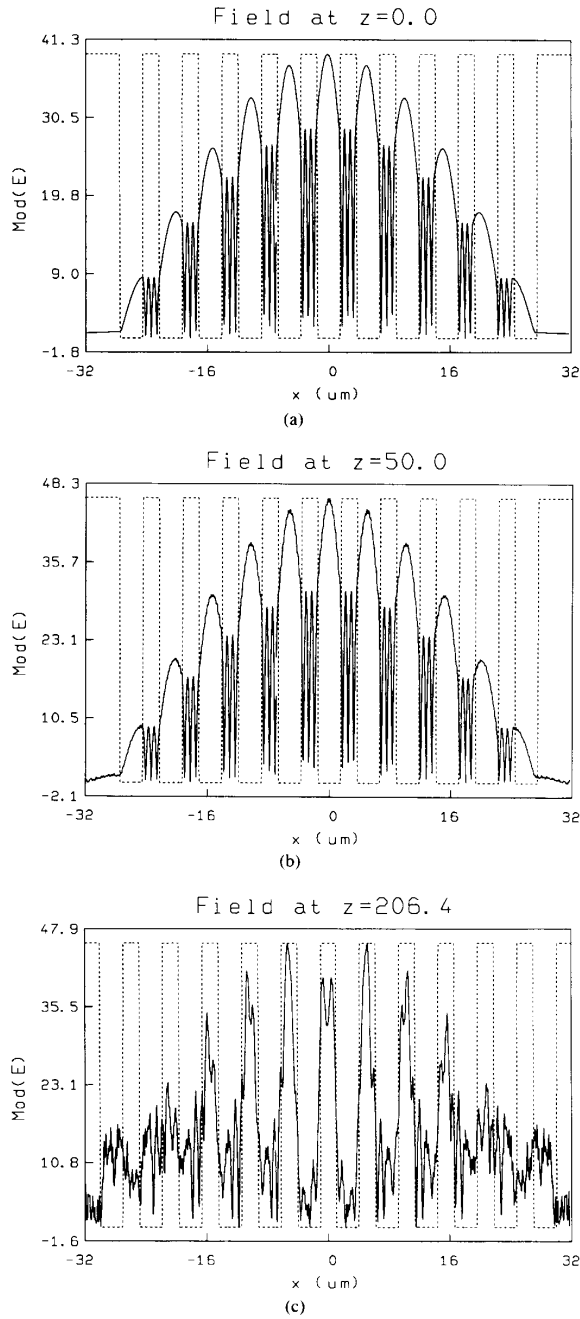


Fig. 6. Intensity profiles of (a) mode 11 at $z = 0 \mu\text{m}$, (b) mode 11 at $z = 50 \mu\text{m}$, and (c) mode 11 at $z = 206.4 \mu\text{m}$. (The dashed lines represent the real refractive-index profile.)

B. Talbot Filtering

In order to analyze the filtering of the eleven array modes by the Talbot filter the field propagation of the modes in an array structure as shown in Fig. 2 was cal-

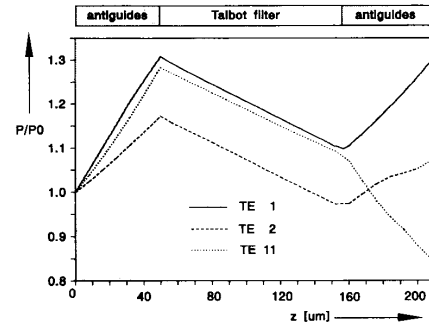


Fig. 7. Total power in the array structure versus z for modes 1, 2, and 11.

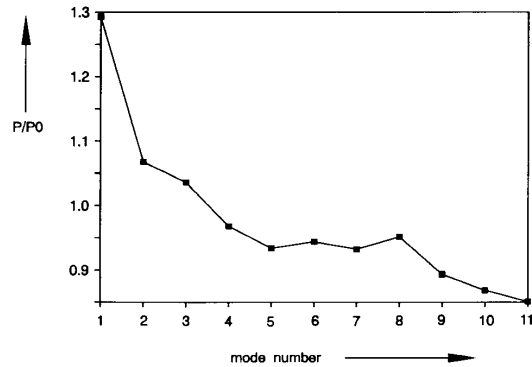


Fig. 8. Ratio P/P_0 of the total power P and the input power P_0 in the array structure at $z = 206.4 \mu\text{m}$ for the eleven array modes.

culated using a program based on the beam-propagation method (BPM) [8]. The BPM is a computational tool widely used in integrated optics and consists of propagating a beam over a small distance through a homogeneous space followed by a correction on the refractive-index variations seen by the beam during the propagation step.

The array modes in a diode laser array are generally polarized parallel to the x direction (Fig. 1) due to reflectances at the mirror facets. Although in our multilayer representation this would result in a TM-like polarization only the effect of the Talbot filter on TE polarized modes was calculated because the BPM does not allow for TM polarization.

Figs. 4, 5, and 6 display the intensity profiles of modes 1, 2, and 11 at the end of the first and the second set of antiguides. The profiles at the end of the first set of antiguides still resemble the initial ones for all three modes. However, at the end of the second set of waveguides modes 1 and 2 will still resemble the initial intensity profiles while the out-of-phase mode, mode 11, appears to be distorted. Most of its intensity is found in the interelement regions, characterized by high losses, which leads to the suppression of this mode.

The fact that the first two modes are not filtered out can also be inferred from Fig. 7, showing the ratio of the total

power in the array structure P and the input power P_0 versus z for modes 1, 2, and 11. Modes 1 and 2 show a power increase in both sets of antiguides, while mode eleven only shows an increase in power in the first set of antiguides. Fig. 8 displays the ratio P/P_0 at the end ($z = 206.4 \mu\text{m}$) of the total array structure for the eleven modes. It clearly shows that not only modes 2 and 11 but also modes 3 through 10 are filtered out effectively.

Although the second mode is not affected by the Talbot filter, which is in agreement with the findings of Botez *et al.* [5], it will be unlikely that the array will operate in this mode since the modal discrimination between modes 1 and 2 at and even close [10] to resonance is very high, as shown in Fig. 3, due to the fact that the second mode suffers more edge-diffraction losses than the in-phase mode [5]. Thus, the array will have a diffraction-limited output since modes 2 through 11 are either filtered out or are prevented from lasing due to a high modal loss.

IV. CONCLUSIONS

An analysis of the Talbot filtering of all the array modes in an ROW array of antiguides has been demonstrated. It has been shown that an ROW array of antiguides with a Talbot filter is an effective means to achieve single in-phase mode operation with a diffraction-limited output.

ACKNOWLEDGMENT

The authors gratefully acknowledge the valuable discussions with H. Martinot, F. Lozes-Dupuy, and H. J. W. M. Hoekstra.

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