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Transverse electromagnetic modes simulation and experimental measurement technique for a single stripe laser diode

Fernando Carlos Romano
Center for Lasers and Applications
IPEN-CNEN/SP
São Paulo, Brazil
fernando.romano@usp.br

Niklaus Ursus Wetter
Center for Lasers and Applications
IPEN-CNEN/SP
São Paulo, Brazil
nuwetter@ipen.br

***Abstract*— A single stripe multimode laser diode software model has been developed. In addition, a method for measuring the transverse electromagnetic modes (TEM) in the RF spectrum through a frequency beating process was also developed. For supporting the TEM readings, a spectrum analyzer was applied and converted the temporal signals to the frequency domain using the fast Fourier transform (FFT) method.**

Keywords*— laser diode, transverse modes, semiconductor laser, multimode laser, laser simulation, broad area laser diode, BALD

I. INTRODUCTION

The core objective of this work is the development of a single stripe broad area laser diode simulation model based on a set of nonlinear and inhomogeneous differential equations, supported by an experimental method providing a consistent method to link with the theoretical physics, simulations, and measurement from the experimental side.

II. SOFTWARE MODEL

The development of an analytical model through a computer program for simulating a single stripe broad area laser diode (BALD) simulates the transverse electromagnetic modes (TEM) exactly from their threshold levels, precisely showing the power pumping level when they start to oscillate in the cavity and calculating the mode individual output power. The numeric model evaluates the BALD output parameters, such as the beam power and its modal oscillation thresholds, calculating the optical power as a function of the transverse individual modes, aiming at knowing when and under what conditions the occurrence of higher order operating modes will occur.

III. MEASUREMENT METHOD

In the experimental section of this work, we demonstrate how two neighboring transverse modes generate a beat frequency in the GHz range, and how this self-heterodyning physics allows to establish a simplified experimental method, using standard electronic instrumentation instead of the much more complicated optical equipment that would be necessary for measurements in the THz regime.

A. Experimental setup

The optical bench setup diagrams used for the experimental tasks are presented in Fig. 1 a. and b. Both topologies have been developed and employed for supporting the fast Fourier transformation (FFT) extractions. In Fig. 1.a the whole laser beam was focused precisely onto the active area of the fast photodetector generating a single point concentrating all the beat frequencies. In Fig. 1 b. the optoelectronic system was prepared for the transverse mode coordinate identification by generating a beam with a stripe geometry and sweeping the detector transversally to the beam, allowing in such way to measure the order of the modes as a function of their transverse coordinate x by using an optical fiber connected to the detector in the focal point of the second lens.

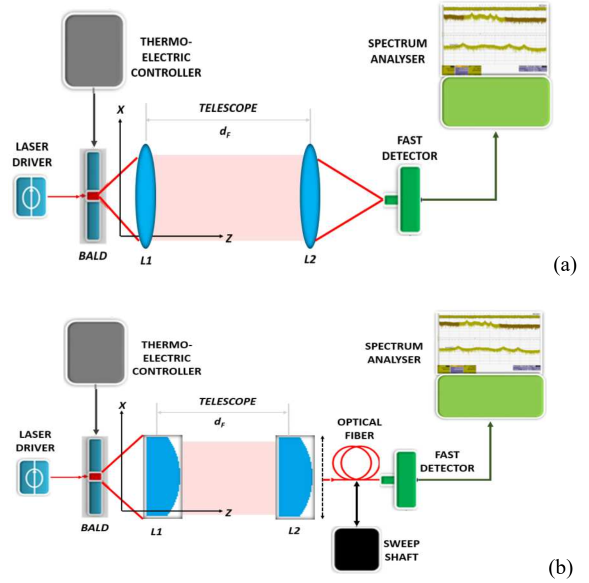

Fig. 1 Experimental setup to measure the TEM. (a) With aspheric lenses to achieve a point focus and to read the beat frequencies of all the modes together. (b) Using cylindrical lenses and a 400 μm aperture optical fiber on a translation stage to measure the coordinates of each transverse mode beating.

In Table I, the indium gallium arsenide (InGaAs) BALD parameters can be observed, those ones used throughout the experiment (main values).

TABLE I. LASER DIODE PHYSICAL PROPERTIES

Parameter	**Description**	**Value [unit]**
λ_o	Center wavelength	830 [nm]
P_o	Output power (continuous wave)	1,0 [W]
$\Delta\lambda$	Spectral width	2,5 [nm]
$d\lambda/dT$	Wavelength temperature coefficient	0,3 [nm/°C]
Slope eff.	Lasing rate	1,0 [W/A]
Mat.	Material and alloy	InGaAs
n_R	Material refractive index	3,34
W	Transversal width	100 [μm]
Y	Cavity height	1 [μm]
Z	Cavity length	4,0 [mm]

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IV. RESULTS

The purpose of this section is to compare the theoretical calculations, simulation outputs, and experimental data, promoting an analysis of the consistency of the results.

A. Simulation results

In this section, we demonstrate some functionalities of the developed synthetic model. In Fig. 2 we have the responses obtained for the first 15 transverse modes, showing their onset threshold (oscillation) in steady state condition, according to the diode current. With this graph, it is possible to observe the individual power level that each mode reaches and operates. The simulation works with cosine and Hermitian modes. As per Fig. 3a. and b. the numeric model determines the transversal distribution of the power from the TEMs inside the cavity for each single transverse mode.

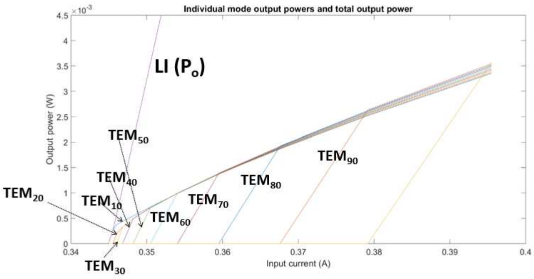

Fig 2. Simulated LI curves for the BALD with responses for the first 15 TEM modes as a function of the pump forward current (IF). The purple trace indicates the total output power of the laser diode.

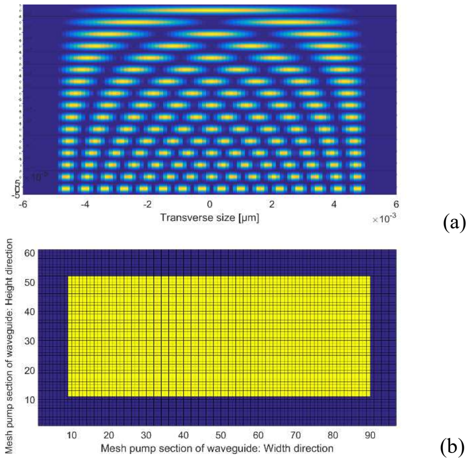

Fig 3. a) From top to bottom: each line represents the transverse intensity distribution of the modes in the semiconductor cavity starting with TEM$_{00}$ (x). (b) Cross section through the BALD showing the electric charge's pump distribution (in yellow).

B. *Mode beat frequencies extraction*

All temporal sensor waveform collections were processed by the digital fast Fourier transform (FFT) through the spectrum analyzer. Measurements of the beat frequencies between two adjacent transverse modes, as a function of the pump current (I_F), are summarized in Table II. In Fig. 4.a. we show an example of setup 1 (figure 1a) showing the FFT of all beat frequencies measured together.

TABLE II. MEASURED BEAT FREQUENCIES, SPHERICAL LENSES

I_F (mA)	Distribution of frequency beats [GHz]				
	$f_{pp'1}$	$f_{pp'2}$	$f_{pp'3}$	$f_{pp'4}$	$f_{pp'5}$
320		1,75	1,90		
340		1,70	1,95		
360	1,25	1,75	2,25	2,65	
380	1,28	1,75	1,90	2,10	
400	1,31	1,75	1,93	2,30	
420	1,35	1,75	2,20	2,32	
440	1,30	1,75		2,38	
460	1,35	1,82	2,25	2,39	
480	1,40	1,80	2,20	2,40	
500	1,35	1,75	2,25	2,45	3,10
520	1,35	1,75	2,25	2,60	3,10
540	1,35		2,25	2,60	3,10
560	1,35	2,25		2,60	
580	1,35	2,30		2,65	

C. *Transverse coordinates extraction*

In Table III the transverse coordinates readings are shown obtained by looking for a specific beat frequency in the transverse beam direction. An FFT sample is shown in Fig. 4.b.

TABLE III. MEASURED COORDINATES, CYLINDRICAL LENSES

I_F (mA)	T_D (°C)	Transverse coordinate (x) occurrence				
		x [μm]	$f_{pp'1}$	$f_{pp'2}$	$f_{pp'3}$	Remark
365	19,5	2800	1,65			Flat op.
365	19,5	2800	1,65			Flat op.
365	19,5	2800	1,65			Flat op.
365	19,5	2900	1,65	1,80		Flat op.
365	19,5	2900	1,65	1,80		Flat op.
365	19,5	3300	1,65	1,80		Flat op.
365	19,5	3600	1,65	1,80		Flat op.
365	19,5	4500	1,65		2,10	Flat op.
365	19,5	4680	1,65		2,10	Flat op.
365	19,5	4990	1,65		2,10	Flat op.
358	19,5	4990	1,65		2,00	Power red.
380	19,5	4990	1,70		1,95	Power inc.
380	19,5	6000			2,30	Power inc.
436	19,5	6080			2,30	Power inc.
450	19,5	6720			2,30	Power inc.
460	19,5	6830			2,30	Power inc.

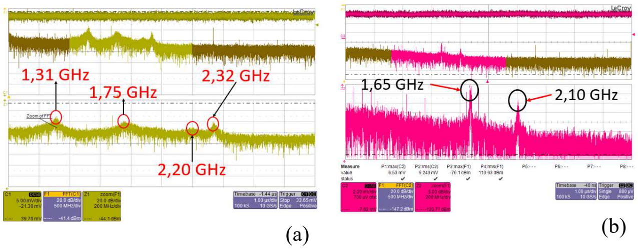

Fig. 4 FFT waveform samples. (a) Identification of several TEM frequency beats obtained with setup of figure 1a. (b) Identification of the frequency beats occurring at position *x* = 2900 μm. I_F = 365 mA, T_{DL} = 19.5 °C using the setup in figure 1b.

CONCLUSIONS

As a primary innovation from the present work, we simulate the oscillation threshold of the transverse modes by applying the rate equations according to the development realized by [1]. The second development is an experimental method for reading the beat frequencies from the transverse modes looking at the FFT spectrum results as a function of their relative positions with reference to their transverse coordinate. Theoretical, simulations and experimental data are mutually agreeing very precisely.

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