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Integral plug-in RF module in a CO_2 hybrid-waveguide laser: Its performance and overall evaluation

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Abstract

This work describes the performance of a compact "in-house built" radio–frequency (RF)-excited CO_2 slab waveguide laser which has the innovation of having a plugged-in RF generator–amplifier module directly connected into the positive electrode of the laser head. The design circuit parameters include a matching circuit and a feed-through element as a whole. The overall laser performance takes into account the waveguide dimension (y-axis) as approximately one-tenth of the free space transverse dimension (x-axis). The optical resonator is calculated to be in the regime of the negative branch for unstable confocal resonators, having focal lengths of $f_1 = 21.49$ cm and $f_2 = 19.39$ cm with geometrical amplification of 1.108. Optical output coupling mirror was set to ~9.7%. The calculated waveguide length is 37.73 cm whilst the total resonator length was adjusted to 42 cm to allow coupling losses less than 1%. The laser operational efficiency was about 12% and the output beam quality of 1.13 which is close to the ideal Gaussian beam. The optical output power was accomplished by playing with different gas compositions to have a final optimized gas proportion of 1:1:2.7:0.3 correspondingly to CO_2, N_2, He and Xe as admixture.

Keywords: Lasers; Carbon dioxide; Waveguide; Slab

1. Introduction

Radio frequency (RF)-pumped CO_2 waveguide lasers have been in use for over 10 or more years ago. This paper, as far as our knowledge is, points out the first note on the integration of a compact RF amplifier–generator [1] into the positive electrode of the laser head, which in turn is the top-roof for the amplifying media waveguide. The outcome presented here does well in a more easy-to-build laser head, from the electrical and optical point of view and design. As our technique of putting all together, RF generator, matching network and the feed-through, inside the laser head, lead us to the need to perform an overall evaluation of the setup performance. The basic expressions for the optical coupling losses are used to set the experimental values in our system. Also, and to be experimentally self-consistent, we need to evaluate the beam quality by fixing our experimental data to the basics for the quality factor M^2. As the RF waveguide lasers are today one of the most utilized systems for industrial applications, we propose to integrate the RF exciter and the amplifying media as one compact unit. CO_2 lasers can be designed to be all metal or hybrid waveguides, using partly metal and partly dielectric materials for their amplifying media. In hybrid design, a dielectric material such as

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Al_2O_3 (dielectric constant $\varepsilon = 9.95$) is employed to form the side walls for the waveguide while the top and bottom sides play the role of metallic electrodes. The main characteristic of a CO_2 slab waveguide laser is that it combines transversally the RF discharge and the optical propagation for the stimulated emission of light. RF discharge generation is quite different from other discharge technologies, not comparable to DC or AC. In view of the fact that RF fluctuates rapidly in time, electrons generated, which form the ionized plasma in the hollow cavity, "virtually" never die. As electrons never reach the metallic electrodes, thus never ablate their surface, CO_2 molecules do not disassociate in time. As a consequence, a longer lasting life for the gas mixture is possible, increasing laser life as long as its inner cavity is less contaminated. In the present work, we designed and built the hybrid-amplifying media by choosing a metallic (Al) roof-and-ground waveguide with dielectric spacers (dielectric constant $\varepsilon = 9.95$) that act as the waveguide walls. Six pairs of coils were symmetrically placed throughout the waveguide electrodes to distribute the inductive coupling and to balance the voltage across the length of the active medium; consequently, we could have a uniform RF discharge inside the whole waveguide media, providing its complete exploitation.

2. Basic concepts

When the walls used to confine the laser media are as close as to start interacting with the laser resonator standing wave, its modal behavior begins to perform different than that for a free space media, as a consequence of the optical interaction on the boundaries. Marcatili and Schmeltzer [2] reported calculations for the allowed propagation modes inside a dielectric waveguide with cylindrical geometry by solving the wave equation for the free space and dielectric boundary conditions. Thus, the field components were coupled to the waveguide walls. Krammer [3] developed a similar mathematical expression for the field (E) and the wave vector ($k = \beta + i\alpha$) on rectangular waveguides and two different materials. Hill [4] simplified Kramer's expressions by taking one of the materials as metal and the other as dielectric. Those expressions are written here in Eq. (1) through (3), where E denotes the polarized field amplitude along the x-axis, $2a$ and $2b$ are the waveguide height and width, while m and n denote the lateral and transverse modes, respectively,

$$E_{mn}(x,y) = (ab)^{-1/2}\left[\begin{matrix}\cos\\ \text{sen}\end{matrix}\left(\frac{m\pi x}{2a}\right)\right]\left[\begin{matrix}\cos\\ \text{sen}\end{matrix}\left(\frac{n\pi y}{2b}\right)\right];\quad m,n = \text{odd, even}, \tag{1}$$

$$\beta_{mn} \approx \frac{2\pi}{\lambda}\left[1 - \frac{1}{2}\left(\frac{m\lambda}{4a}\right)^2 - \frac{1}{2}\left(\frac{n\lambda}{4b}\right)^2\right], \tag{2}$$

$$\alpha_{mn} \approx \frac{m^2}{a}\left[\frac{\lambda}{4a}\right]^2 \mathrm{Re}\left(\varepsilon_a(\varepsilon_a - 1)^{-1/2}\right) + \frac{n^2}{b}\left[\frac{\lambda}{4b}\right]^2 \mathrm{Re}\left((\varepsilon_b - 1)^{-1/2}\right), \tag{3}$$

where α refers to the phase and β is the attenuation constant.

The overall round-trip optical waveguiding losses, Γ_w, can be calculated using the expression

$$\Gamma_w = 1 - |e^{-j2l\alpha_{m,n}}|^2, \tag{4}$$

where l is the length of the waveguide and $\alpha_{m,n}$ is the attenuation constant given by Eq. (3). Boulnois and Agrawal [5] have derived an approximation from the diffraction integral for the calculation of the coupling losses, which is written as

$$\Gamma_c = 1 - [c_{mm}c_{nn}]^{1/2}, \tag{5}$$

where

$$c_{mm} = \left(1 - \frac{m^2}{6N_m^{1.5}} - \frac{\pi m^4}{240N_m^{2.5}} + \frac{m^4}{72N_m^3}\right)^2 \text{ and}$$
$$c_{nn} = \left(1 - \frac{n^2}{6N_n^{1.5}} - \frac{\pi n^4}{240N_n^{2.5}} + \frac{n^4}{72N_n^3}\right)^2, \tag{6}$$

with $N_m = a^2/4z\lambda$ and $N_n = b^2/4z\lambda$, where a is the height (gap), b the width, z the mirror separation from the waveguide, λ the laser wavelength, m the lateral mode number and n the transverse mode number. This approximation is valid for $N > 1$ and has an accuracy 0.5% for $N = 1$. Hill [4] also calculates the allowed mode frequency for the waveguide resonator, Eq. (7), where j is the longitudinal mode number and c the speed of light. If one compares the relationship between the frequency of the fundamental mode in a free space laser (first term from Eq. (7)) and the frequency in a waveguide laser, it will be easy to note how the allowed mode density in the waveguide is much higher than that in a free space laser with the same length. This characteristic leads to a more efficient gain media in a laser, thus leading to higher output powers [6],

$$\nu_{j,mn} \approx \frac{jc}{2L} + \frac{c\lambda}{8}\left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right). \tag{7}$$

One practical rule to decide if a particular system acts like a hollow waveguide is to fulfill the condition $N < 10$, where N is the Fresnel number given by ($a^2/\lambda l$). Here, λ is the wavelength and l is the waveguide length. For a fundamental Gaussian beam, its propagation is completely characterized by the beam waist, w_0, and waist position, z_0. The beam radius as a function of z, $w(z)$,