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Waveguide polarization and mode selection technique for CO_2 laser

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Abstract

To address the simultaneous demands for high mode quality and polarization stability in the laser applications market, a CO_2 diffusion cooled gas laser operating at the 600W level is presented using a novel planar waveguide surface made from a combination of dielectric and metallic areas. The dielectric generates sufficient higher order mode waveguide loss to ensure only lowest order, fundamental mode oscillation, whilst the metallic area provides enough polarization selectivity to ensure a linearly polarized output. Experiments to optimize the metallic area while maintaining high levels of waveguide mode selection have resulted in metallic lengths between 5 and 30% of the waveguide that extend across its entire width. A ZnSe Brewster window operating with a small offset away from Brewster's angle to sample the beam demonstrates a laser that always operates in the expected TE mode while giving highly stable linearly polarized light at a purity > 5000:1.

Keywords: waveguide; mode; polarization stability; selectivity

1. Introduction

Recent years have seen a growth in applications for compact diffusion cooled planar waveguide CO_2 lasers that require higher levels of mode and polarization purity maintained over increasing process durations. Two examples of this are the 3D engraving of print rolls and surface textured molds that rely on stable beam properties over part cycle times lasting up to hours in duration. Resolution for these applications is often achieved via fast switching of the beam using an acousto-optic-modulator needing the laser to also operate as a high purity linearly polarized source. In the kiss-cutting of labels both low and high average power regimes are used needing a very stable mode insensitive to changes in thermal loading of the laser, while power sampling and beam splitting applications require highly stable polarized sources.

Traditional methods to generate lowest order waveguide mode in CO_2 lasers have centered upon two different approaches. In all metal waveguides the general approach has been to utilize coupling losses at the waveguide ends to select fundamental oscillation. As described in Degnan and Hall, 1973 for circular waveguides there are three low loss cases. Cases III and II have the mirrors placed at a half and a full radius of curvature from the waveguide ends. This approach does not result in a compact design and only case III gives effective lowest order mode selection. Case I is for large radius mirrors placed very close to the waveguide end giving very little mode selection. Here the second approach to waveguide mode selection is generally applied, which uses a dielectric waveguide surface to select the fundamental mode as described in Laakmann and Steier, 1976 for hollow rectangular dielectric waveguides. This approach does result in excellent mode selection in a compact design, but polarization purity has sometimes been found to be an issue.

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2. The planar waveguide diffusion cooled CO_2 laser design

Fig. 1 shows the basic arrangement of a planar waveguide diffusion cooled CO_2 laser. A radio frequency gas discharge is generated between two parallel water-cooled electrode plates. The plates form a planar waveguide while also acting as heat exchangers for the gas discharge. Spherical radius of curvature mirrors placed a few millimeters from the ends of the waveguide (near Case I) form an unstable negative branch resonator in the wider free space dimension, w, while in the narrow dimension, a, waveguiding occurs, with ‘a’ ranging from 1 to 3mm. Light initiates on the optical axis and is magnified on each round trip before exiting around the edge of the output coupler mirror, it then leaves the gas vessel through a transmissive window before external correction optics filter and circularize to form a round near Gaussian beam.

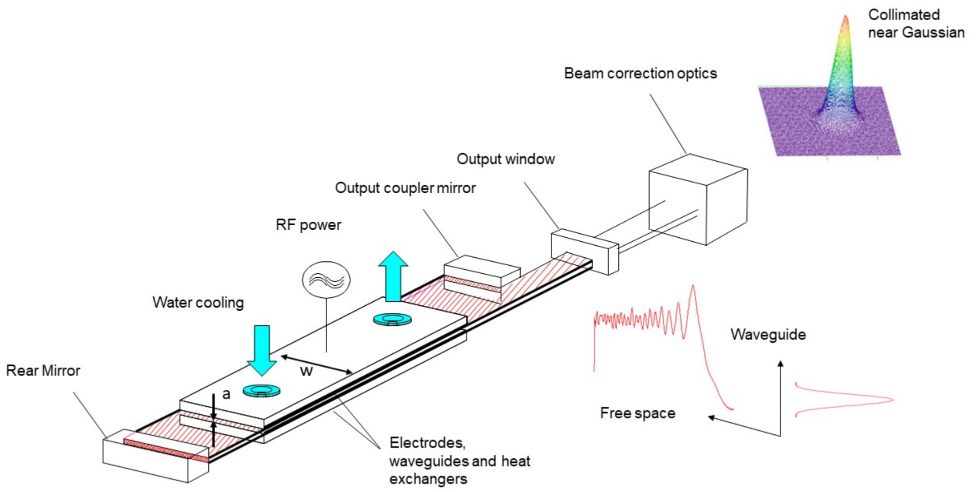

Fig. 1. A schematic of the basic workings of a planar waveguide diffusion cooled CO_2 laser

The mode exiting the resonator in the free space direction is a high Fresnel-number top hat profile with a near flat phase front defined by the magnification and physical apertures within the resonator, whereas waveguide mode quality and laser polarization are parameters determined by the interaction of the beam with the electrode surfaces. In this paper and as described in Dyer et al., 2017, we investigate a novel planar waveguide design comprising surfaces with both dielectric and metallic sections to give oscillation in the fundamental waveguide mode while guaranteeing stable linearly polarized output.

3. The planar waveguide surfaces

3.1. Waveguide mode selection

The mode or mixture of waveguide modes oscillating in near Case I is dominated by the propagation loss coefficients inside the waveguide compared with the small signal gain. For TE modes (polarization vector parallel with the planar waveguide surfaces) the expression for the loss coefficients taken from Cao et al., 2001 is given below in (1).

$$\alpha_{TE} = \frac{m^2 \lambda^2}{2a^3} Re\left[\frac{1}{\sqrt{(n-ik)-1}}\right] \qquad (1)$$

Here m is the transverse mode order number, λ is the wavelength, a is the separation between the guiding surfaces, n is the refractive index and k is the extinction coefficient of the guiding surfaces.

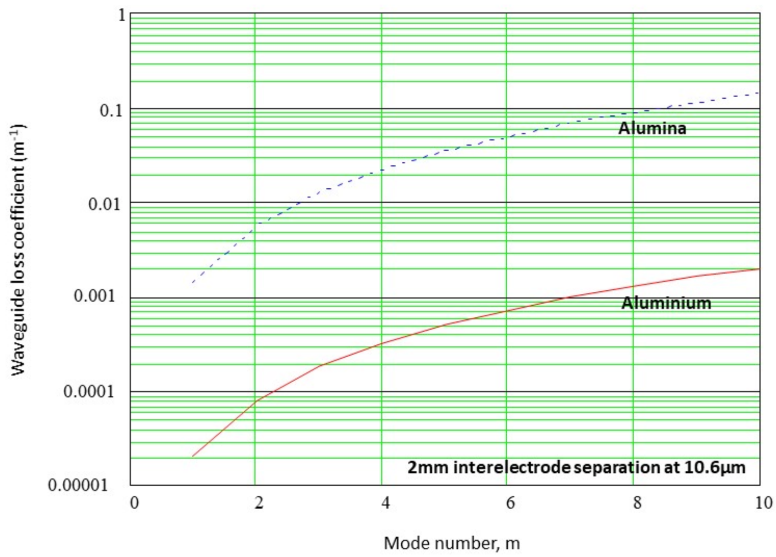

Fig. 2. TE waveguide loss coefficients, α_{TE}, against mode number for alumina and aluminium waveguide surfaces at 10.6um and a 2mm separation

Fig. 2 displays calculated TE waveguide loss coefficients for both alumina and aluminium waveguide surfaces for a propagating wavelength of 10.6um with a 2mm separation between the waveguide surfaces. The different values of refractive index and extinction coefficient taken Khelkal and Herlemont, 1992 and Ordal et al., 1983 are given below in Table 1. For alumina, the lowest order mode, m=1, α_{TE} is ~0.0014m^{-1}, or ~0.15 to 0.3% of typical small signal gain, g_0, which usually ranges from 0.5 to 1.0m^{-1}, whereas for m=3, α_{TE} is ~0.0126m^{-1}, or ~1.25 to 2.5% of g_0. The difference in loss coefficients is sufficient to suppress higher order mode oscillation while allowing efficient lowest order mode operation. In contrast, for aluminium both m=1 and m=3 waveguide order modes are < 0.04% of g_0, resulting in little, if any mode selection.

Table 1. Refractive index and extinction coefficient for alumina and aluminium at 10.6um, from Khelkal and Herlemont, 1992 and Ordal et al., 1983

Material	Refractive index (*n*)	Extinction coefficient (*k*)
Alumina	0.67	0.136
Aluminium	36.6	111

3.2. Polarization selection

For TM modes (polarization vector perpendicular with the planar waveguide surfaces) the expression for the loss coefficients taken from Cao et al., 2001 is given below in (2).

$$\alpha_{TM} = \frac{m^2\lambda^2}{2a^3} Re\left[\frac{(n-ik)^2}{\sqrt{(n-ik)-1}}\right] \quad (2)$$

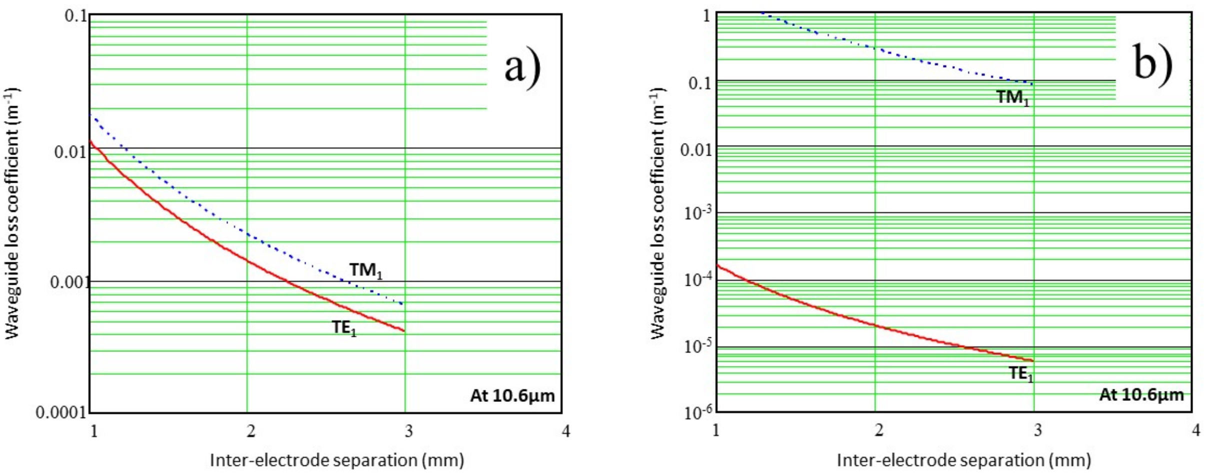

Fig. 3. (a) TE and TM lowest order waveguide loss coefficients against separation for alumina at 10.6um; (b) values for aluminium

Fig. 3a displays calculated lowest order TE and TM loss coefficients for alumina guiding surfaces against waveguide separation. At a separation of 2mm, the loss coefficient for TE mode is $0.001m^{-1}$ and for TM mode $0.002m^{-1}$. While the loss for TM mode is twice that of TE, the loss never exceeds 0.4% of g_0, leading to insufficient preferential laser oscillation on a particular polarization. Fig. 3b displays the same lowest order loss values, but this time for aluminium guiding surfaces. For TE mode the loss coefficient is ~$0.00002m^{-1}$, ~0.004% of g_0, whereas for TM mode the loss coefficient is ~$0.28m^{-1}$, ~60% of the small signal gain coefficient, g_0, resulting in very strong polarization selectivity.

3.3. Design concept

The different loss coefficients calculated for alumina and aluminium are typical of the values obtained for a range of dielectric and metallic surfaces. Dielectric waveguide surfaces are ideal for lowest order waveguide mode selection but cannot guarantee strong polarization selectivity, whereas metallic surfaces are poor regarding mode selectivity, but naturally select TE mode polarization orientation. The proposed design therefore looks to combine the benefits of both material types by using a dielectric waveguide surface that includes a small metallic region.

Fig. 4 shows the proposed design for the planar waveguide surface, with a planar view and a cross-section through both electrodes about the optical axis, OA. For the planar view the free space forward-planar and reverse-focusing / diverging wave fronts are represented. The metallic section of length, L_M, extends across the entire width, w, but only between 5 and 30% of the waveguide surface length, with the majority of the waveguide surface comprising 2 dielectric sections represented by lengths L_{D1} and L_{D2}. This is possible because the lowest order TM loss coefficient for a continuous metallic surface is ~$0.28m^{-1}$, 60% of the small signal gain, g_0, 10 to 20 times higher than required to ensure exclusive oscillation of TE modes, since higher order TE modes are suppressed at loss coefficients of only ~2% of g_0. Therefore, through the use of a small localized metallic region the TM polarization loss coefficient can still be at a level to guarantee TE polarization, ~2% of g_0, while the remaining dielectric surface coverage ensures lowest order waveguide mode oscillation.

To form the metallic region, there are several approaches. The first involves inserting a machined metallic block into a machined ceramic component. The supporting structure can be either metallic or dielectric. The second approach involves coating a localized metallic region of several microns thickness onto a ceramic substrate. Finally, a metallic substrate can be coated with a dielectric coating of several microns thickness with a region masked off so that bare metal is exposed to the oscillating light.

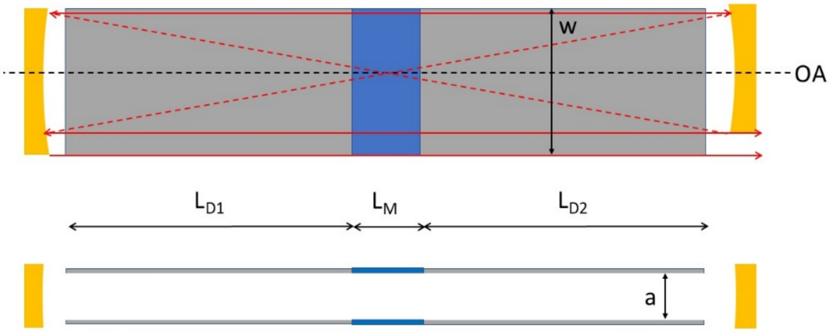

Fig. 4. Proposed planar waveguide design, planar view and cross section through both electrodes about the optical axis, OA

4. Experimental Results

A planar waveguide diffusion cooled CO_2 laser operating at the 600W average power level was built with dielectric extending over the entire waveguide surface. Assessment of the waveguide mode showed the expected lowest order mode and excellent stability with time. To assess polarization purity, the filtered and circularized beam was directed onto a ZnSe plate inclined at an angle of incidence a few degrees away from Brewster's angle. Here, the reflectivity for p-polarized light from the plate is ~0.5 to 1.0%, whereas the reflectivity for s-polarized light is ~60%. With the TE mode polarization vector orientated along the s-polarized direction, any change in polarization will result in a significant change in the ratio of power reflected to that transmitted through the plate. Fig. 5a shows that that with no metallic polarizing region, there are clear spikes in the reflected signal, demonstrating the polarization is changing state between TE and TM modes.

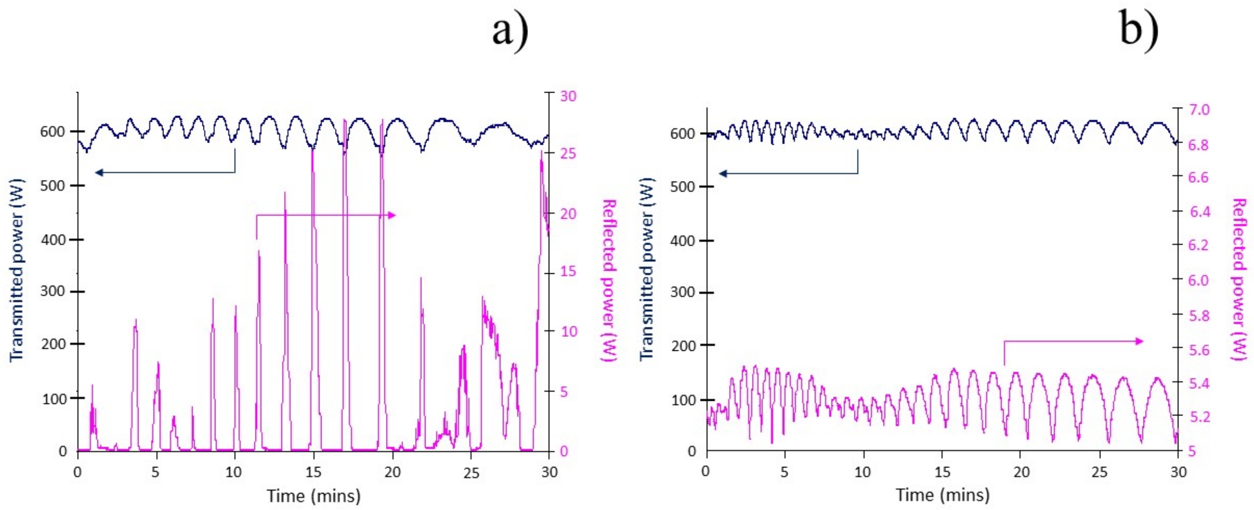

Fig. 5. (a) Powers from a ZnSe plate for a laser having a dielectric waveguide with no metallic region; (b) with a metallic region covering 5% of the surface

To generate stable polarization, a metallic region was added. The region extended the entire waveguide surface free space dimension, w, and was placed centrally about the free space reverse wave focus to give 5% coverage of the waveguide surface area. Fig. 5b shows a reflected power that is a directly scaled replica of the transmitted beam power. Given the differences in reflectivity for p and s-polarized light and the normalized reflected and transmitted powers vary by less than 0.4% over the entire 30-minute run, the data relates to a stable polarization purity of > 5000:1. To assess mode quality, beam radius measurements were recorded through the focus of a 1.3m lens. Values for the free space direction are shown in Fig. 6a while those for the waveguide are in Fig. 6b. For both directions the beam quality factor, M^2, has a value of 1.05, clearly demonstrating that both high polarization purity and high-quality mode are possible simultaneously with this novel design approach.

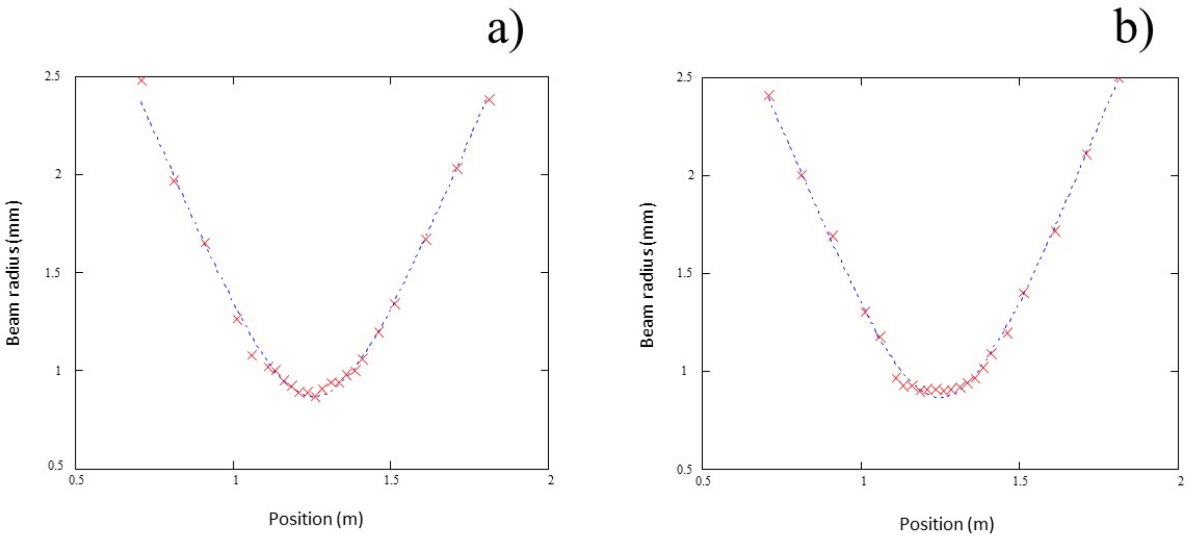

Fig. 6. (a) Free space beam radius measurements from a laser having a dielectric waveguide with a metallic region covering 5% of the surface; (b) waveguide beam radius measurements

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