High power coupled CO_2 waveguide laser array

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A hollow-bore ridge waveguide technique for phase locking arrays of coupled CO_2 rf excited waveguide lasers was demonstrated. Stable phase-locked operation of two- and three-channel arrays has been demonstrated at the 50 W output level. Preliminary experiments with a five-element array generated an output power of 95 W but phase-locked operation was not conclusively demonstrated.

During the past few years, rapid progress in phase-locked diode laser arrays has resulted in higher coherent output power than is obtainable with single diode lasers. Recently, this general concept was applied to CO_2 waveguide lasers in which a two-element array was phase locked at the 1 W output power level by optically coupling the two laser elements through a transparent partition.[1] Here we report phase-locked operation of two- and three-element CO_2 waveguide laser arrays at the 50 W output power level using a new guide structure, analogous to dielectric and microwave ridge waveguide structures, which we have termed a hollow-bore ridge waveguide. This structure appears to have a number of advantages relative to the transparent partition structure such as ease of fabrication, compatibility with high thermal conductivity ceramics, and easily controlled optical coupling between array elements, which are features that enhance the likelihood of developing practical CO_2 waveguide laser arrays.

The concept of coupled hollow-bore ridge waveguides and the technique used to rf excite the CO_2 laser mixture within the waveguides are illustrated in Fig. 1(a). The waveguides are formed by grinding slots into an Al_2O_3 ceramic slab and then placing this slab between rf electrodes. Optical coupling between waveguides is achieved by shortening the partition between elements to form a gap of dimension a, permitting radiation in a waveguide to leak into adjacent waveguides. The coupling between waveguides is controlled by adjusting both the gap dimension a and the separation b between waveguides. Typical waveguide dimensions for CO_2 waveguide lasers range between 1×1 mm^2 and 3×3 mm^2. In the present work, the waveguide dimensions were fixed at 2.25×2.25 mm^2 and the waveguide length was fixed at 37 cm. The $He:N_2:CO_2:Xe(6:1:1:0.25)$ laser mixture at 100 Torr pressure under a sealed-off condition was excited with a transverse 147.5 MHz rf discharge. The techniques used to efficiently couple rf power into the active medium and to uniformly excite the active medium along the entire length of the waveguide array have been described elsewhere.[2,3] The waveguide array structure was placed within a water-cooled aluminum vacuum housing which incorporated an rf feedthrough to enable power to be transmitted to the array structure. The resonator was formed by placing a flat common output mirror ($R = 0.9$) and a flat common reflector ($R = 0.995$) within a few millimeters of each end of the waveguide array. The resonator mirrors were attached to the aluminum housing with mounts that permitted angular adjustments in the two orthogonal axes (x and y) perpendicular to the optical axis (z). One mirror mount also incorporated a piezoelectric transducer for fine control of the optical resonator length.

Two waveguide geometries, as illustrated in Fig. 1(b), were evaluated. The first consisted of an array of conventional square-channel waveguides and the second consisted of an array of half-round half-square hybrid waveguides which we have termed a U-channel waveguide. For a given gap and separation, it was found that the two waveguide geometries performed equally with regards to laser output power and phase locking. However, the U channel has the advantage

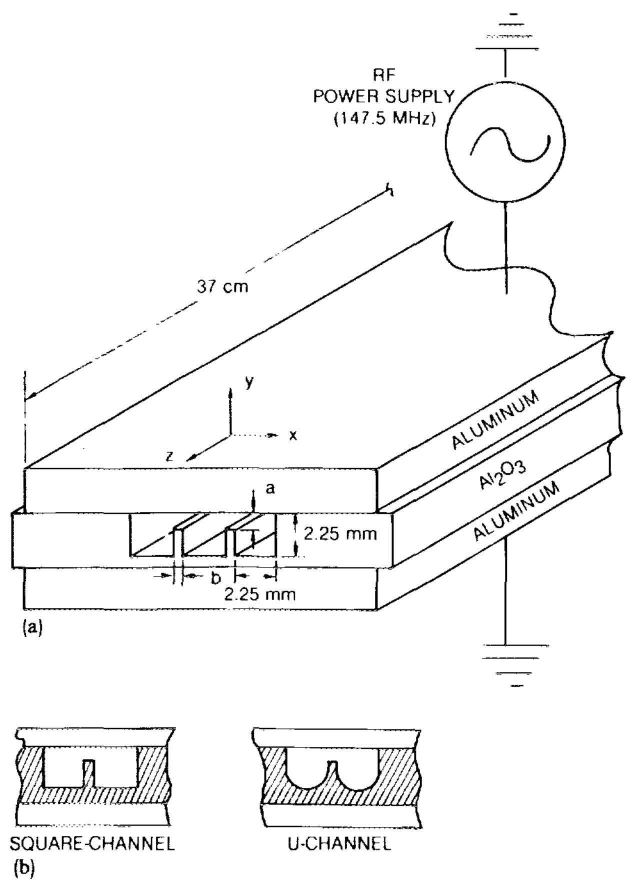

FIG. 1. (a) Schematic representation of a three-element coupled ridge hollow waveguide laser array with rf excitation. (b) Cross sections of the two waveguide geometries studied in this investigation.

that smaller separations between waveguide elements can be achieved because of the additional support provided by the thicker base of the partition. Because of this advantage, the results reported here are limited to those obtained with the *U* channel.

The diagnostics used during this study consisted of measuring (1) the total power of the array, (2) the operating rotational transition(s), (3) the beat frequency between waveguide elements using a high-bandwidth detector, and (4) far-field intensity profiles along the *x* axis, as defined in Fig. 1(a), by scanning the beam across a detector with a 1-mm aperture.

The first issue investigated was whether high optical extraction efficiency could be achieved with a coupled hollow-bore ridge waveguide array. To address this issue, an experiment was conducted in which the output power of a two-element array was measured as a function of the gap size for a fixed separation of 0.5 mm. For a single-element waveguide laser, an optimum output power of 25 W was measured with an rf pump power of ~250 W. Thus, a 50-W output would be expected for a two-element array if there were no degradation in performance. Under the condition of zero gap, a 50-W output for a two-element array was obtained with an rf input of ~500 W, demonstrating no loss in output power due to the close proximity of the waveguide elements. As the gap size was increased from zero to 1.13 mm (i.e., 1/2 the channel dimension), the output power decreased to 42 W or 21 W per element corresponding to about a 15% decrease in output power. Furthermore, in a very recent unoptimized experiment, a five-element array with a 1.13-mm gap generated 95 W or 19 W per element corresponding to about 80% of the maximum power that could be expected. While undesirable, this power loss is small enough to permit a substantial improvement in total output power to be realized with a waveguide array relative to that which can be generated by a single waveguide element and demonstrates that the coupled hollow-bore ridge waveguide is compatible with high optical extraction efficiency even for a gap as large as one-half the waveguide dimension.

The second area of the investigation concentrated on first demonstrating and then characterizing phased-locked operation. In the first experiment, the far-field on-axis intensity was monitored as a function of the beat frequency between the array elements of a two-element laser array in which the gap and separation were 1.12 and 0.25 mm, respectively. The beat frequency or oscillating frequency difference between the two waveguide elements was adjusted by introducing a slight tilt of the output mirror where *y* is the axis of rotation [see Fig. 1(a)]. This results in a slight change in the round trip optical path length for the two array elements and, therefore, a slight change in their individual operating frequencies. At beat frequencies of approximately 12 MHz and greater, the on-axis intensity was a constant function of the beat frequency. As the beat frequency was adjusted to approximately 11 MHz, the beat frequency vanished and the on-axis intensity doubled indicating single-frequency phase-locked operation had been achieved. Single rotational line operation always occurred under these conditions. Furthermore, intensity profiles of the far-field mode pattern were generated and compared to theoretical predictions as shown in Fig. 2.[4] Under the condition of beating between the waveguide elements, the far-field intensity profile was in the form of a Gaussian as shown in the incoherent case of Fig. 2. When the output mirror was adjusted such that the on-axis intensity was maximized, the phase-locked symmetric mode profile in Fig. 2 was obtained. In this case, the electric fields in the two guides are in phase and therefore produce an on-axis maximum in the far field. It is important to note that the symmetric mode was easily obtained in this investigation which may be a result of higher gain for this mode due to gain in the gap region. By further adjusting the output mirror, the phase-locked antisymmetric mode, in which the electric field in the two waveguide elements are 180° out of phase, was also observed and its measured intensity profile is shown in Fig. 2. When the mirror tilt was adjusted to achieve phase-locked operation in either the symmetric or antisymmetric mode, the phase-locked state could be maintained for hours with only a cavity length adjustment with the piezoelectric driven mirror. While a detailed comparison of the experimental and theoretical intensity profiles in Fig. 2 reveals that there are differences between the two, such as the spatial separation of the maxima and the relative amplitudes of the maxima (especially in the case of the antisymmetric mode), there is good agreement in the general shape of the profiles. The above results combine to clearly demonstrate that stable phase-locked operation of a coupled hollow-bore ridged waveguide array has been achieved.

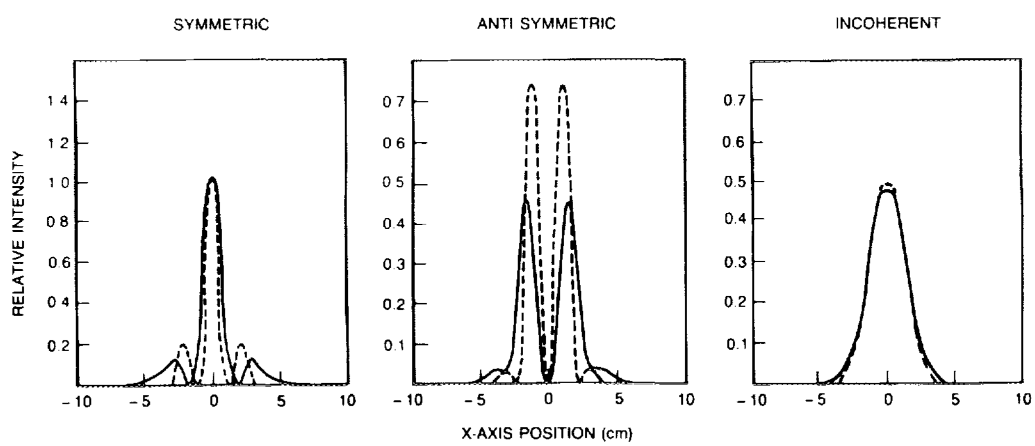

FIG. 2. Solid curves are the measured far-field intensity profiles along the *x* axis (see Fig. 1) for a two-element array at ~6 m from the array output. Note that the sensitivity of the detector preamplifier has been increased for the antisymmetric and incoherent cases. Dashed curves are the theoretical predictions of the far-field beam profile for the above experimental conditions.

The minimum beat frequency discussed above is related to the locking range in which a larger minimum beat frequency corresponds to a larger locking range which in turn results in a more stable phase-locked array output. Therefore, a parametric study was conducted with a two-element array in which the observed minimum beat frequency was determined as a function of the gap and separation dimensions. Because the locking range increases with increased coupling, increasing the gap and decreasing the separation results in more coupling between elements and an increase in the minimum beat frequency, as shown in Fig. 3. For gap dimensions larger than 1.4 mm, it was found that single frequency operation could not be achieved. Also note the zero separation case was made possible through the use of the *U*-channel waveguide geometry.

One three-channel waveguide was fabricated and tested with gap and separation dimensions of 1.14 and 0.25 mm, respectively. Phase-locked operation was conclusively demonstrated in a manner identical to that used for the two-element array. In the case of the three-element array, the minimum detected beat frequency was 9 MHz, the phase-locked symmetric mode was clearly the preferred mode of operation and the output power was supply rf limited to 55 W. It was estimated with a near-field burn pattern that individual waveguide element intensities were within 20% of each other.

As discussed previously, a very recent experiment was conducted with a five-element array with gap and separation dimensions identical to the three-element array. Although interference fringes were observed, the fringe contrast was not nearly as well defined as for the two- and three-element cases. We are therefore drawn to the conclusion that only partial phase locking was achieved in this case. Further experiments are in progress.

In conclusion, stable phase-locked operation of two- and three-element ridge CO_2 waveguide laser arrays has been demonstrated at the 50 W output level. Phase-locked operation was maintained for many hours in a laboratory environment without adjustments other than length tuning of the array laser, a condition which clearly demonstrates the practicality of this phase-locking technique. A five-element array produced a 95-W output but phase-locked operation was not conclusively demonstrated. With further development, we project that very compact single-frequency CO_2 waveguide laser arrays with output powers well above 100 W, a value much higher than that typical of present single-channel waveguide lasers, may be realized using the coupled hollow-bore ridge waveguide technique.

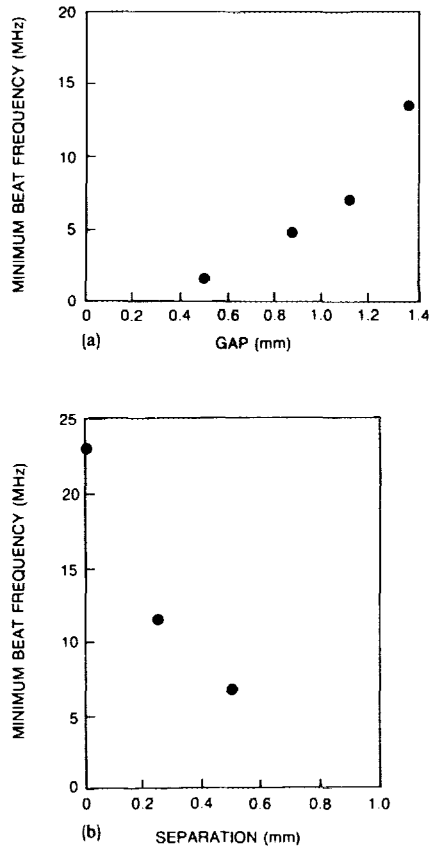

FIG. 3. (a) Measured minimum beat frequency between the elements of a two-element array as a function of the gap dimension for a fixed separation of 0.5 mm. (b) Minimum beat frequency as a function of the separation for a fixed gap of 1.13 mm.

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