

MID-INFRARED OPTICALLY PUMPED, UNSTABLE RESONATOR LASERS (Preprint)

A.P. Ongstad et al.

31 May 2007

Journal Article

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.



**AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 31-May-2007		2. REPORT TYPE Journal Article		3. DATES COVERED (From - To) 01-December-2006 – 21-March-2007	
4. TITLE AND SUBTITLE MID-INFRARED OPTICALLY PUMPED, UNSTABLE RESONATOR LASERS (Preprint)				5a. CONTRACT NUMBER In-House(DF297213)	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62605F	
6. AUTHOR(S) A.P. Ongstad, R. Kaspi, G.C. Dente*, M.L. Tilton*, J. Chavez*				5d. PROJECT NUMBER 4866	
				5e. TASK NUMBER LY	
				5f. WORK UNIT NUMBER 12	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFRL/DELS 3550 Aberdeen Avenue Kirtland AFB, NM 87117-5776 *Boeing Defense & Space Group Albuquerque, NM 87106				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory 3550 Aberdeen Avenue SE Kirtland AFB NM 87117-5776				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-DE-PS-JA-2007-1012	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Submitted for publication in Applied Physics Letters, 90, 191107, (2007) American Institute of Physics					
14. ABSTRACT The authors describe high-brightness, broad area midinfrared semiconductor lasers. These devices were fabricated in the authors' laboratory using a commercial solid-source molecular beam epitaxial system. The laser structures incorporated 14 type-II quantum wells embedded in thick waveguide/absorber regions composed of In _{0.2} Ga _{0.8} As _{0.18} Sb _{0.82} . The optically pumped devices achieved higher brightness operation as unstable resonators. Each unstable resonator was realized by polishing a diverging cylindrical mirror at one of the facets. For an unstable resonator semiconductor laser operating at $\approx 4.6 \mu\text{m}$, near 84 K, and at a peak power of 6.7 W, the device was observed to be nearly diffraction limited at 25 times threshold. In comparison, a standard Fabry-Pérot laser was observed to be many times diffraction limited when operated under similar conditions					
15. SUBJECT TERMS antimonide, mid-infrared lasers, W laser, optically pumped semiconductor laser, quantum wells, waveguide loss, internal efficiency, gain, empirical pseudopotentials, hole leakage, hole dilution, thermal degradation					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			Dr. Andrew Ongstad
			Unlimited	13	19b. TELEPHONE NUMBER (include area code)

Mid-infrared, optically pumped, unstable resonator lasers

A. P. Ongstad and R. Kaspi, . *Air Force Research Laboratory, Directed Energy Directorate AFRL/DELS, 3550 Aberdeen Ave. Kirtland AFB, NM, 87117*

G. C. Dente, M. L. Tilton, and J. Chavez
Boeing Defense and Space Group, Albuquerque, NM 87106

We describe high-brightness, broad-area mid-infrared (IR) semiconductor lasers. These devices were fabricated in our laboratory using a commercial solid-source molecular beam epitaxial (MBE) system. The laser structures incorporated fourteen type-II quantum wells embedded in thick waveguide/absorber regions composed of $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}$. The optically pumped devices achieved higher brightness operation as unstable resonators. Each unstable resonator was realized by polishing a diverging cylindrical mirror at one of the facets. For an unstable resonator semiconductor laser operating at $\sim 4.6 \mu\text{m}$, near 84 K, and at a peak power of 6.7 W, the device was observed to be nearly diffraction limited at 25 times threshold. In comparison, a standard Fabry-Perot laser was observed to be many times diffraction limited when operated under similar conditions.

High power optically pumped mid-IR lasers have been demonstrated with peak powers in the 5 to 15 W range, CW powers in excess of 2 W and lasing wavelengths in the 2 to 10 micron region.^{1,2} However, these broad area lasers typically display degraded beam quality as the pump intensity is increased; they may go from 2-3 times diffraction-limited near threshold to 8-15 times diffraction-limited at ~ 30 times threshold. This limits the devices applicability since it becomes difficult to couple the radiation into a small aperture fiber or to focus the radiation in the far field. There are a large number of applications that would directly benefit from high power mid-IR output with a nearly diffraction limited beam. These applications include infrared countermeasures, free-space optical communication, remote sensing, laser marking, and various medical applications.

A number of approaches have been utilized in near-IR semiconductor diode lasers to achieve high-power operation with diffraction limited output. These include tapered amplifiers³, angled injection into traveling wave or reflective wave amplifiers⁴, coupled narrow stripe lasers, and various unstable resonator (UR) geometries^{5,6}. The UR laser concept is best understood by comparing it to the conventional Fabry-Perot (FP) laser. The conventional semiconductor laser uses an FP cavity defined by two parallel facets. The lasing mode undergoes multiple reflections at the cavity mirrors and the mode is directly counter-propagated. In contrast, the UR laser is characterized by counter-propagating diverging cylindrical waves diverging from fixed virtual source points. By avoiding direct counter-propagation UR's suppress filamentation and maintain excellent beam quality with all the radiation diverging from fixed high-brightness virtual source points. Consequently, the UR laser is a true high brightness source since near diffraction-limited beam quality can be

preserved even with broad laser cavities and under conditions of high current injection or optical pumping.

Lasers were epitaxially grown in our laboratory using a commercial solid-source molecular beam epitaxy system, configured specifically for antimonide alloy deposition. Heterostructures were deposited on 2 in. diameter (001) oriented GaSb:Te substrates. The laser design incorporates 14 type-II quantum wells that are placed 1000 Å apart in a 1.5 μm thick InGaAsSb waveguide. Two factors serve to reduce filament formation or antiguiding in these antimonide based “W” lasers. First, the lattice-matched GaSb clad layers provide only a small difference in the index of refraction relative to the waveguide ($\Delta n \approx 0.03$) such that the optical mode has very weak transverse confinement. These low confinement factor or “dilute” waveguides tend to suppress filament formation and allow for high brightness operation. Specifically, as the confinement factor, Γ , is lowered the filament gain decreases far more rapidly ($\approx \Gamma^2$) than does the modal gain which decreases in a linear manner⁷. A typical confinement factor for a telecommunications based GaAs laser would be $\Gamma \approx 0.020$ whereas we employ significantly smaller gammas, $\Gamma \approx 0.003$ -0.004. The second feature leading to a reduced tendency to form optical filaments are the intrinsically low antiguiding factors found in the optically pumped semiconductor (OPSL) heteroepitaxy. Indeed, Hakki-Paoli measurements of the antiguiding factor, α , for these quantum well lasers have yielded consistently low alpha values with $\alpha \leq 1$ ⁸.

Consequently, the implementation of a dilute waveguide structure, coupled with a low antiguiding factor epitaxy suggests that the application of a lateral mode control element, such as that embodied by an unstable resonator, may be highly effective for this class of W laser. Moreover, such a design may yield broad area mid-IR semiconductor lasers capable of both high power output and excellent lateral beam quality with operation near the diffraction limit.

The optically-pumped UR's are realized by mechanically polishing a diverging cylindrical mirror on one facet of a Fabry-Perot laser cavity. The chip is affixed onto a platform where it is mechanically polished using a rotating circular pad. This results in a high-quality cylinder with the desired radius of curvature and minimal facet damage. To assess mirror quality a Zygo Newview 6k optical profilometer was employed. Detailed scans of the polished mirrors show that high quality cylindrical figures are formed with a radius of curvature near 10.0 mm. Further, the scans reveal relatively minor surface abrasion; the scratches and digs are on the order of 38 nm or $\approx 1/30^{\text{th}}$ wave. The relative high quality of the curved facet reduces scattering and helps preserve the output power characteristics of the device. The output power for an OPSL UR emitting near 4.6 μm and operating near 84 K is shown in figure 1; the maximum output power for the UR is 6.63 W slightly less than a comparable Fabry-Perot laser which delivered 7.62 W of peak power for a 32 μs pulse (1 % duty cycle) This modest 14 % drop in power is largely attributable to the extra loss of the cavity due to geometric magnification of the radiation. This resonator magnification, M , is conveniently quantified as:

$$M = \frac{V + L}{V - L} = \frac{\sqrt{L^2 + RL} + L}{\sqrt{L^2 + RL} - L}$$

where L is the cavity length and R is the cylindrical mirrors radius of curvature. For a typical polished device with $R = 10$ mm and $L = 3.5$ mm the magnification factor is 3.1; for reference the FP cavity has a $M = 1$.

The regenerative reimaging of the circulating radiation is the critical mechanism leading to high brightness from the virtual source point. These virtual source points, shown as V_+ and V_- in figure 2, are located at a distance $V = \pm \sqrt{L^2 + LR}$ from the flat facet. The left virtual source, V_+ , is at an object distance $(V+L)$ from the diverging mirror with focal length

(-R/2). Upon reflection from the curved facet, the radiation forms a virtual image, V_* , at a distance (V-L) to the right of the curved facet.

In actual operation, the radiation is outcoupled from the flat facet, so that the virtual waist of the lateral mode is located behind the output facet at a refractively reduced distance, $D = V/n$, in which the index of refraction is given by $n = 3.82$. For a typical device geometry this reduced distance is inside the device at approximately 1.810 mm from the flat facet. The size of the diffraction limited waist, or spot diameter, is given by: $S_D = 2 \times \lambda \times F/\#$, where $F/\#$ is the resonator f-number and is simply the ratio of the distance back to the virtual source, D , to the pump stripe width, w ie.- $F/\# = D/w$. In addition to the high brightness generated by the regenerative reimaging of the virtual source points, the natural divergence of the propagating mode tends to mitigate self-focusing or filamentation, leading to further brightness improvements ⁷.

Figure 3 shows a comparison of best-focus points for a Fabry-Perot device and for a mid-IR unstable resonator device, both devices operating near 4.6 μm and pumped at 25 times above threshold. . Figure 3a shows the best-focus reimage results for the FP cavity operating at $\approx 30 \times$ threshold; a degraded best-focus is evident. In comparison, a very clean virtual source spot with a full-width diameter of 70 μm is apparent in the UR image of Figure 3b. For the UR device, the far-field is realized by reimaging the virtual source points located a distance D from the flat facet. The measured diameter is close to the calculated diffraction limited spot diameter of $S_D = 67 \mu\text{m}$. In addition, the virtual waist was located at a distance, $D = 1.835 \text{ mm}$, back from the flat facet, very close to the value predicted from geometrical theory, ie.- $D = V/n = 1.810 \text{ mm}$.

Longer wavelength UR's have also been fabricated and characterized. For a 9.13 μm emitting UR, at the maximum pump power of 43 W, the 3.5 mm long device delivered nearly 2.5 W of peak power. The virtual source was measured at 1745 μm back from the flat

facet with an approximate diameter of $120\text{ }\mu\text{m}$; consequently, the resonator is operating near the diffraction limit at $\approx 42 \times$ threshold.

In summary, higher brightness operation is obtained from antimonide based W lasers by forming an unstable resonator cavity. The UR is realized by mechanical polishing a cylindrical mirror on one of the facets. Inspection of the mirrors using a Zygo profilometer reveals the formation of a high quality cylindrical mirror with a radius of curvature of $\approx 10\text{ mm}$. The 3.5 mm long UR's set up a virtual source points near $1810\text{ }\mu\text{m}$ back from the flat facet in good agreement with theory. Both $4.6\text{ }\mu\text{m}$ and $9.13\text{ }\mu\text{m}$ resonators were demonstrated to operate near the diffraction limit at $25 \times$ and $42 \times$ threshold, respectively. The small optical confinement and small linewidth enhancement factors of these lasers undoubtedly contribute to the ability of the UR to maintain the lateral beam-quality. However, it is likely that the UR approach would be suitable for a wider range of semiconductor lasers including mid-IR, electrically injected quantum cascade lasers.

References

- 1) R. Kaspi, A.P. Ongstad, G.C. Dente, J.R. Chavez, M.L. Tilton, and D.M. Gianardi, Applied Physics Letters; 2006; vol.**88**, no.4, p.41122-1-3.
- 2) *Mid-Infrared Semiconductor Optoelectronics*, A Krier (Ed.), Springer-Verlag, London, 2006, pp. 303-321,
- 3) J.N. Walpole, Opt. Quant. Electron., 1996, **28** (6),623-645.
- 4) L. Goldberg, D. Mehuys, and D.C. Hall, Electronics Letters; 1992; vol.**28**, no.12, p.1082-4.
- 5) M.L. Tilton, G.C. Dente, A.H. Paxton, J. Cser, R.K. DeFreez, C.E. Moeller, and D. Depatie, IEEE J. Quantum Electron., 1991, **27** (9), 2098.
- 6) S.T. Srinivasan, C.F. Schaus, S.Z. Sun, E.A. Armour, S. D Hersee, and J.G. McInerney, Appl. Phys. Lett., 1992, **61**, 11, 1272.
- 7) Dente, G. C., IEEE J. Quant. Electron. 2001, **37** (12), 1650.
- 8) Antiguiding in mid-IR optically pumped semiconductor lasers, in preparation, 2007.

Figure Captions

Figure 1. Peak power-power curves for $L = 3.5$ mm long Fabry-Perot and Unstable Resonator lasers operating near $4.6 \mu\text{m}$ and 84 K. To minimize thermal load on the laser the curves were collected under pulsed conditions: 32 μs pulse, 1 % duty cycle.

Figure 2. Schematic of unstable resonator showing virtual source points V_+ and V_- . L is the resonator length (3.5 mm), R is the radius of curvature of the polished cylinder ≈ 10 mm, w is the stripe width (FWHM = 250 μm) and D is the refractively reduced distance to the virtual source, $D = 1810 \mu\text{m}$.

Figure 3a. Re-image of degraded best-focus at $30 \times$ threshold for the Fabry-Perot laser.

Figure 3b. Re-image of virtual source at $25 \times$ threshold for the $4.6 \mu\text{m}$ UR. The virtual source size indicates the lateral mode is nearly diffraction limited

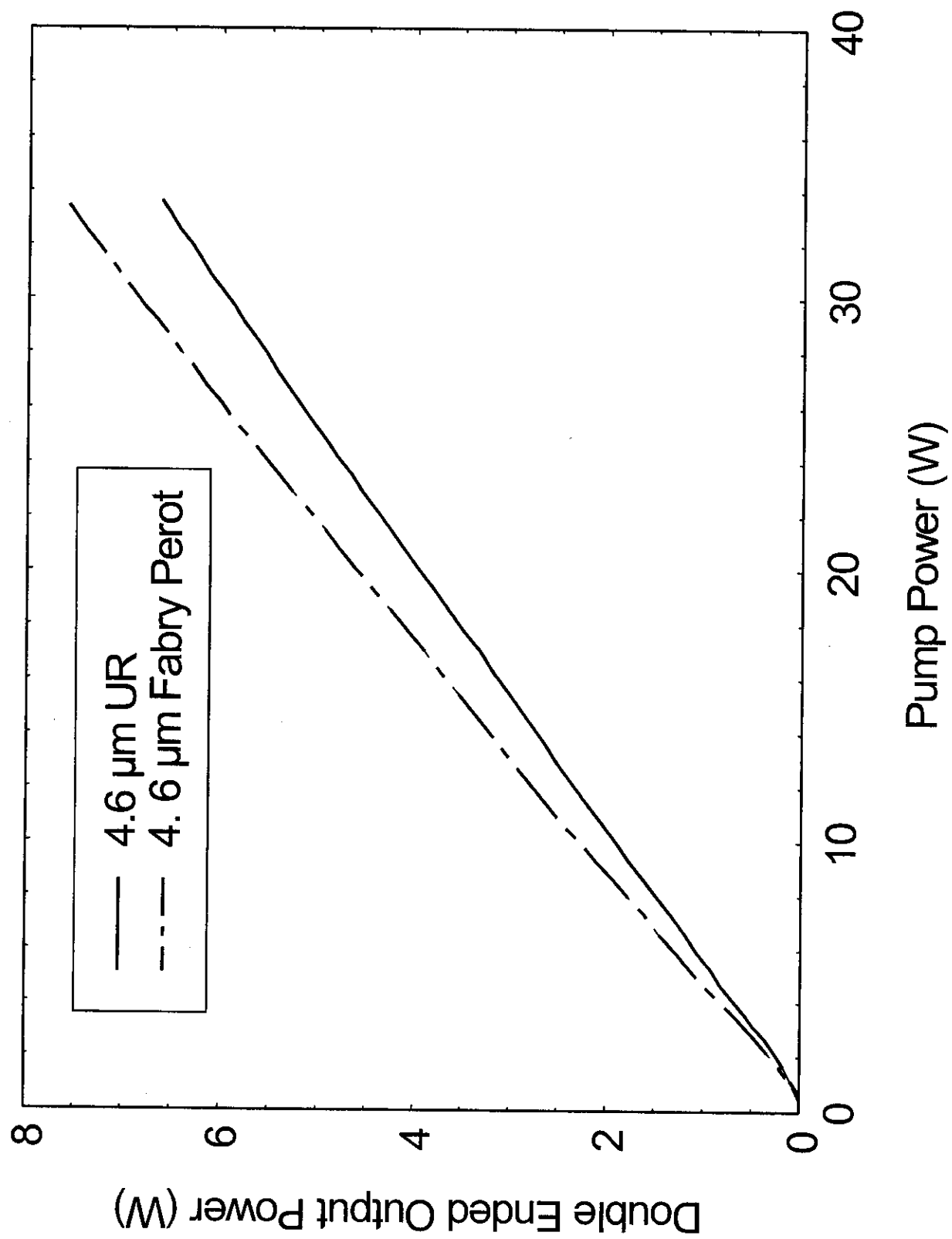


Figure 1.

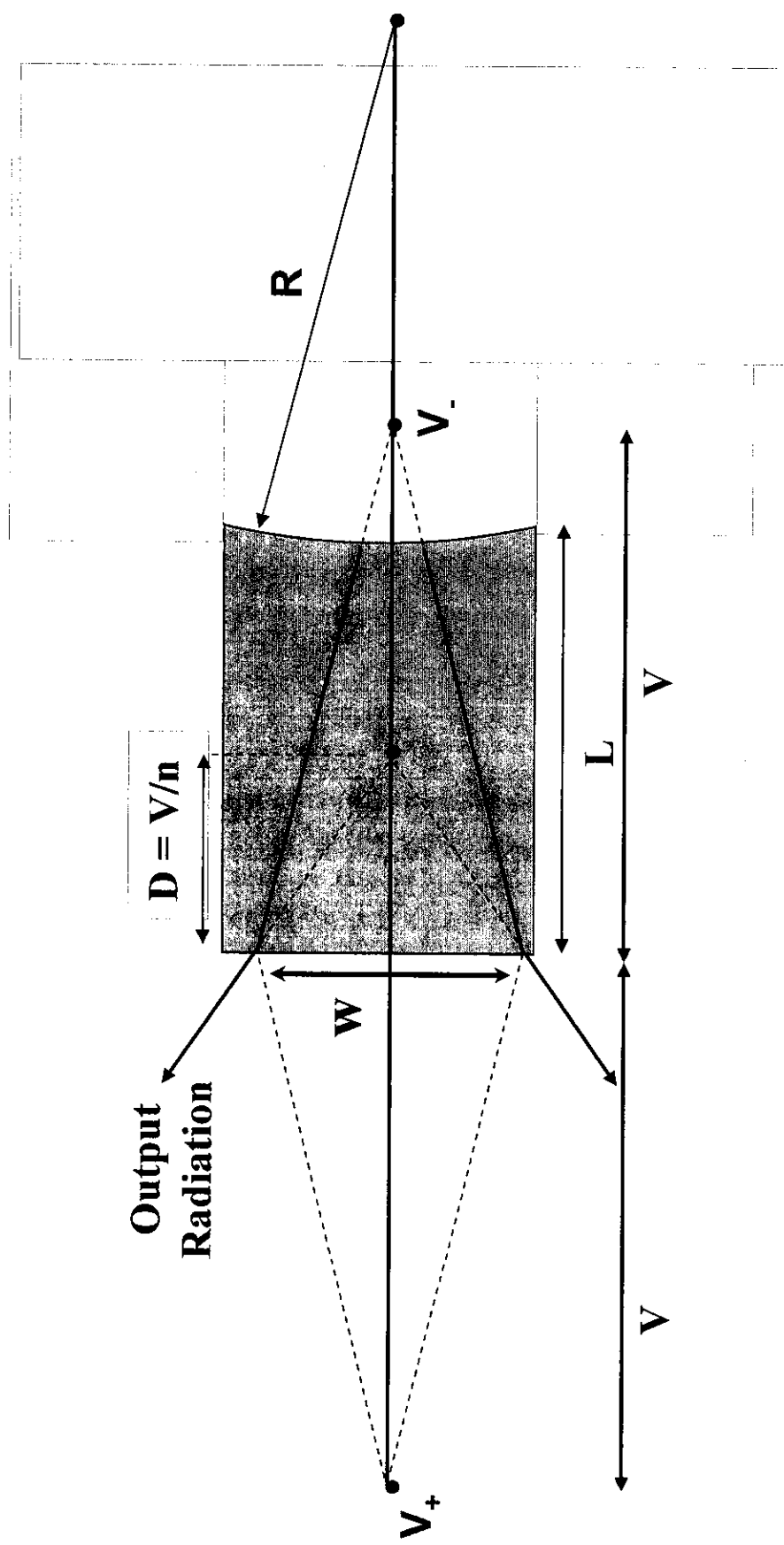


Figure 2.

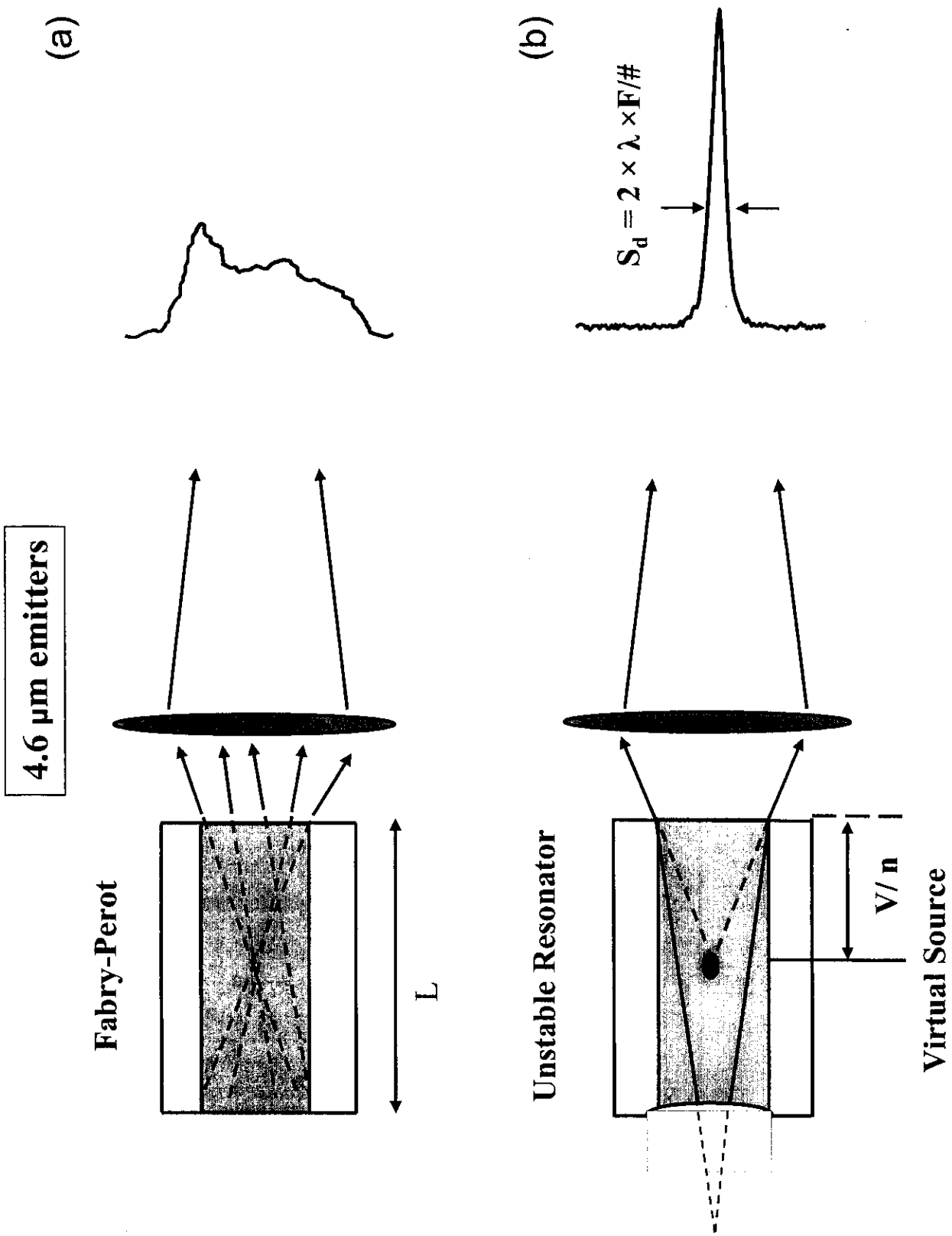


Figure 3.