

Performance of a Modified Negative Branch Confocal Unstable Resonator for COIL

Juergen Handke

DLR, Institute of Technical Physics, Langer Grund, 74239 Hardthausen, Germany

Thomas Hall

DLR, Institute of Technical Physics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

Carsten Pargmann, Karin M. Gruenewald, Frank Duschek

DLR, Institute of Technical Physics, Langer Grund, 74239 Hardthausen, Germany

Far field deployment of high power chemical oxygen iodine laser (COIL) affords optimally adapted resonator architectures. Such resonators shall enable high brightness operation. The different resonator concepts suffer from the low gain medium and the rectangular geometry typical of COIL. Even full exploitation of the laser active medium yields small outcoupling fractions and in consequence small magnifications for unstable resonator design. Additionally, the realization of suitable aspect ratios for the output aperture is difficult. An off-axis modified confocal negative branch unstable resonator (MNBUR) is recommended for high power COIL. For first verification tests, such a resonator is especially designed and coupled to a medium-sized COIL. Near field and far field characteristics are measured and compared to the theoretical predictions. The results and experiences gathered at the 10 kW-class DLR-COIL are encouraging to recommend MNBUR as a well suitable resonator for tactical COIL systems.

I. Introduction

SINCE COIL is capable to generate high brightness radiation, the main challenge is to pick out the appropriate resonator architecture. Different resonator types were successfully designed^{1,2} and applied to COIL^{3,4,5}. The deployment of COIL as a tactical system imposes additional requirements on the resonator concept like compactness and mechanical stability.

Efficient power extraction from COIL allows only low values for output coupling, due to the COIL inherent low gain medium. A stable resonator with a high Fresnel number results in a multi-mode operation with poor beam quality. For unstable resonators with low gain, the total coupling loss has to be small⁶. In consequence, the magnification M , i.e. the ratio of the radii of curvature of back mirror R_{BM} and output mirror R_{OM}

$$M = \frac{R_{BM}}{R_{OM}}$$

has to be close to 1 for typical COIL systems. The result is a far field intensity distribution with a lot of structure and a very small peak power. Hence, a conventional unstable resonator⁷ is not well suited for this type of laser.

In a first step, DLR applied a negative branch hybrid resonator NBHR⁸ that is optimally adapted to a medium-sized COIL. Unfortunately, the hybrid resonator suffers from two shortcomings. The cylindrical mirrors are of special design and therefore cost-expensive and of extended delivery periods. Additionally, the beam quality in stable direction decreases with increasing mirror dimensions. However, for 10 kW-class systems the hybrid resonator is convincing in performance.

Outcoupling restrictions are released for a COIL of higher power. The low gain is partially compensated by a larger volume of the active medium. Therefore, the amplification is increased and higher values of magnification are suitable. For real high power systems (MW-class) completely unstable resonator configurations are well adapted for high brightness emission. But still at the 100 kW level the magnification is rather small resulting in a strongly structured far field intensity distribution. In addition, high brightness emission also implies to extract as much power from the laser as possible. The spherical geometry of conventional unstable resonators is not well adapted to the

rectangular geometry of a COIL gain medium. An off-axis modification of the classical resonator configuration proves to be easily adaptable to COIL geometry while simultaneously reducing the far field intensity structures.

Irrespective of the fundamental demand for high brightness, the resonator architecture of a tactical system is affected by non-optical requirements concerning its applicability under field conditions. The resonator shall consist of a minimum number of optical components with little engineering effort. Special emphasis is given to a reproducible and reliable resonator performance, the simplicity of resonator alignment, and the susceptibility to environmental distortions.

II. Resonator Features and Properties

The MNBUR layout is based on the classical confocal unstable resonator⁹ that is outlined in figure 1a. The radii of mirror curvatures are given by R . The resonator length is L . The indices OM and BM symbolize the output and the back mirror, respectively. The modification of the conventional unstable resonator is performed by a modification of the shape of the resonator mirrors (figure 1b).

The ring-shaped out-coupling of a NBUR is changed to a half-ring aperture of about the same aperture area but with a better balanced aspect ratio. The width of the emitted ring structure is increased. Thereby, the off-axis modification significantly reduces the intensity distribution structures in the far field⁹. Such a resonator is presented in figure 1b. In addition, the MNBUR is less sensitive to misalignment than the NBUR.

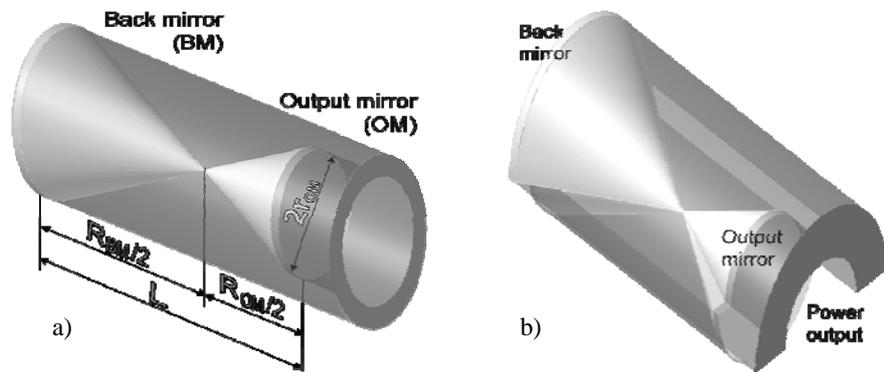


Fig. 1: Conventional negative branch confocal unstable resonator NBUR (a) and Modified negative branch confocal unstable resonator MNBUR (b)

A comparison of total coupling losses depending on the mirror tilt is given in figure 2. FPR symbolizes a Fabry-Perot resonator behavior, α and β describe the tilt angles of output mirror and back mirror, respectively.

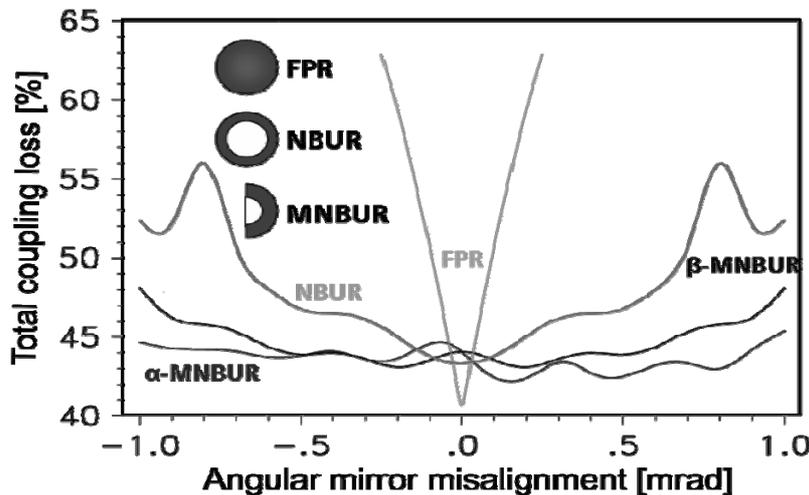


Fig. 2: Comparison of alignment sensitivities of FPR, NBUR, and MNBUR, in the latter case concerning output mirror (α) and back mirror (β).

The improvement of the far field intensity distribution can be derived from figure 3.

Additional modifications are necessary to adapt the circular resonator to a rectangular geometry. Due to the inherent excitation processes of a COIL, the optimum shape of optical access to the active medium is rectangular^{10, 11}.

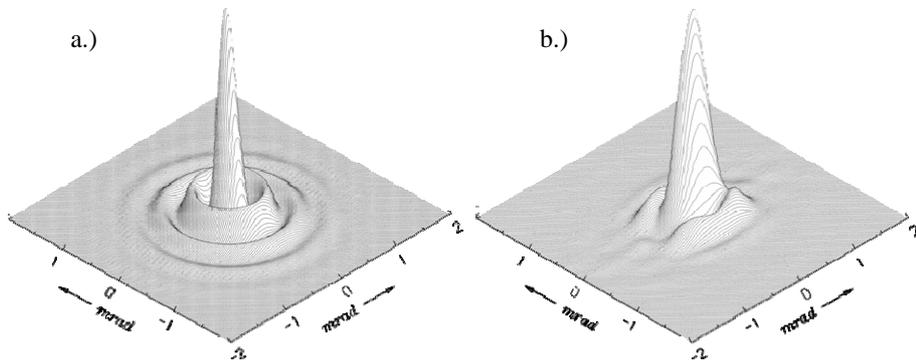


Fig. 3: Comparison of far field distributions generated by conventional (a) and modified (b) negative branch unstable resonator

The off-axis modification as well as the adaptation to the rectangular geometry can be performed by a sophisticated mirror design or by using classical spherical mirrors and a particularly designed scraper. Following the demands for simplicity and cost-effectiveness, two classical spherical mirrors were applied together with a scraper configuration. The mirrors are commercially available. The manufacturing of the scraper is straight forward. The chosen assembly is outlined in figures 4 and 5. The requirements of the MNBUR yield a laser output beam in a characteristic [-shape.

The focal points of both mirrors coalesce inside the negative branch resonator. For COIL conditions, the focal point can be positioned outside the cavity. An intra-cavity breakdown is not to be expected. In addition, preliminary tests with a focal line positioned even within the cavity didn't show any negative effect on the laser-active medium nor on the beam quality⁸.

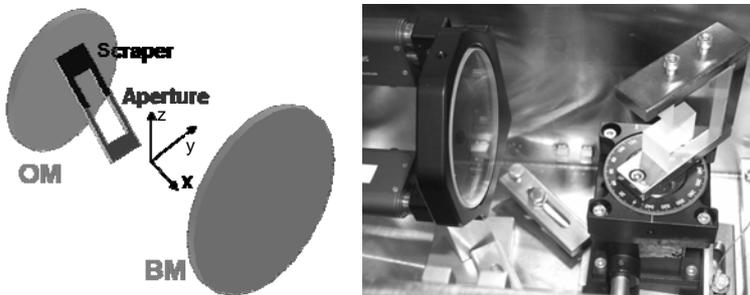


Fig. 4: Sketch and photograph of the realization of a MNBUR for a rectangular laser configuration

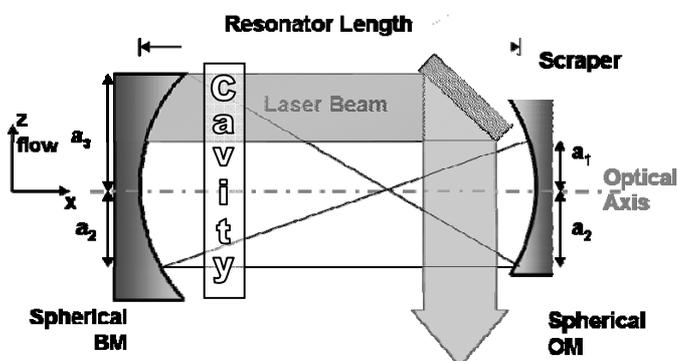


Fig. 5: MNBUR configuration

The resonator layout and the theoretical performance predictions are based on the solution of the Fresnel-Kirchhoff formulation of Huygens¹² principle by the method of Fox-Li¹³. The formulation is applied to a passive resonator^{14,15}.

While this resonator type is originally designed for a high power COIL, the verification tests have to be performed at an only medium-sized COIL because of availability. Therefore, MNBUR has to meet the restrictive outcoupling conditions of that smaller power class. The resulting resonator performance will only provide the bottom limit of the resonator properties to be expected in the appropriate power level. The presented data are based on the 10 kW-class DLR-COIL device.

Figure 6 shows the amounts of total coupling loss (including diffraction losses and output coupling), output coupling, and geometrical output coupling, each depending on the magnification. Based on the Rigrod curve fitted to former experimental results with a

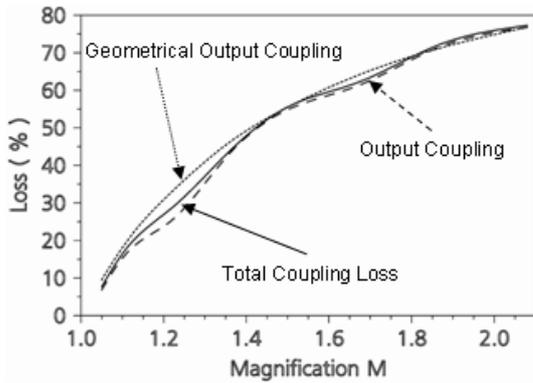


Fig. 6: Total coupling loss and output coupling of the MNBUR versus M

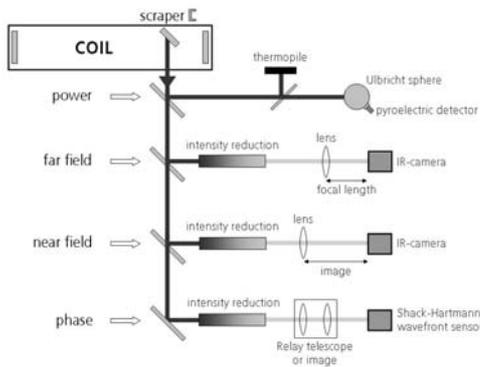


Fig. 7: Experimental set-up

imaged to the chip of a CCD camera (Spiricon, COHU4812 or SCOR20). The same cameras are used for far field measurements in the focal plane of a lens. Additionally, the wave front is monitored in the near field. The optical image for wave front detection is produced by help of a Relay-telescope. The wave front measurement is performed by a specially designed Shack-Hartmann-sensor (SHS) based on a Spiricon COHU4812 camera. The Spiricon cameras are well adapted for the COIL wavelength.

IV. MNBUR Performance

For MNBUR prealignment, a HeNe laser beam is coupled by a pellicle to the resonator axis. The spherical resonator mirrors are aligned coaxial and positioned for confocal set-up. Now, the HeNe laser beam is expanded in

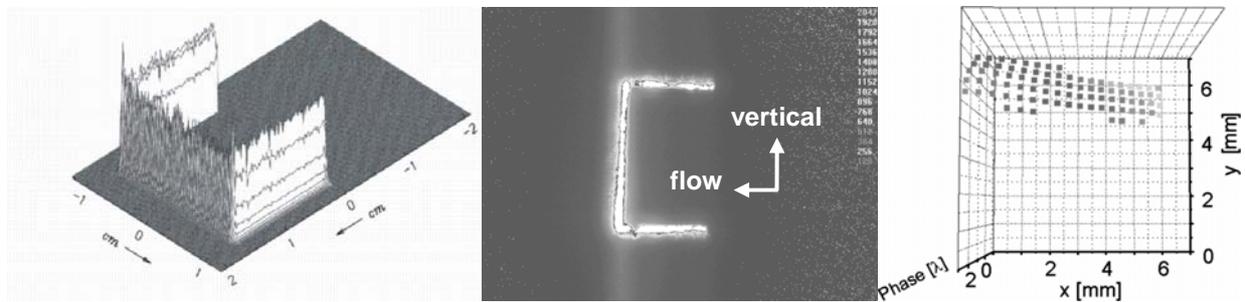


Fig. 8: Basic description of the MNBUR by calculated near field intensity distribution (left), 2-D measured near field intensity profile (center), and measured wave front (right)

stable resonator at the DLR-COIL¹⁶, a total coupling loss of 4-10 % is recommended. A first very conservative approach for the MNBUR leads to an optimum magnification number of 1.05. The numerical calculation of the optimum resonator yields a total coupling loss of 5.3 % and an output coupling of 4.8 %. The nominal resonator length is set to 2 m.

III. Experimental Set-up

The above described resonator is coupled to the DLR-COIL device. The technically realized magnification achieved a value of only 1.04 as a consequence of manufacturing deviations concerning the mirror specification. Due to the smaller magnification, the diffraction structures in the far field will increase in comparison to the original layout. The actual resonator length is adapted to a value of $L = 1.98$ m corresponding to the real radii of curvature for the output mirror $R_{OM} = 1.95$ m and for the back mirror $R_{BM} = 2.03$ m. Mirrors and scraper are high reflectivity coated for COIL wavelength. The exploited gain medium is 19.5 mm in height and 21.2 mm in flow direction. The cavity is positioned on the back mirror side behind the focal point. The outcoupling is performed against flow direction as outlined in figure 5.

The experimental set-up is represented in figure 7. The power output is measured by two fast detectors coupled to an integrating sphere and a power meter for calibration. The near field intensity distribution is

diameter and the scraper is inferred at an angle of 45° to the resonator axis in front of the output mirror. The correct positioning of the scraper relative to the optical axis in vertical and in flow direction is verified by imaging the geometry of the HeNe laser beam leaving the resonator. The fine alignment is performed with COIL radiation using an automatically controlled positioning system.

First information on alignment accuracy is gained by analyzing the near field properties. Figure 8 compares calculated and measured values. A 3-D plot of the calculated near field intensity distribution is shown to the left while the corresponding measured values are shown as 2-D plot in the center, both for a perfectly aligned scraper. The contour plot of the measured profile exhibits a 45° -mapping of the scraper contour. The same contour can be derived from the calculated profile.

Figure 8 also includes the corresponding measured wave front profile (right). In order to achieve a reasonable resolution, only part of the total emitting area of MNBUR is imaged to the SHS detector. In figure 8 the upper right part of the near field emission is presented.

While figure 8 shows an almost perfect image of the [-shaped scraper, the beam contour in figure 9 is more similar to an Ω . This variation follows from a misalignment of the scraper. The scraper is moved relative to the optical axis in flow direction. Since the mirrors are larger than the scraper, additional area of radiation field is released. Thereby, two additional side wings appear resulting in the Ω -like shape. When the scraper is misaligned in the opposite direction, as shown in figure 10, parts of the nominal radiation field are shaded by the scraper. These areas cannot longer contribute to the oscillation and the corresponding beam shows reduced width in the upper and



Fig. 9: Basic description of misaligned MNBUR, scraper misaligned in flow direction

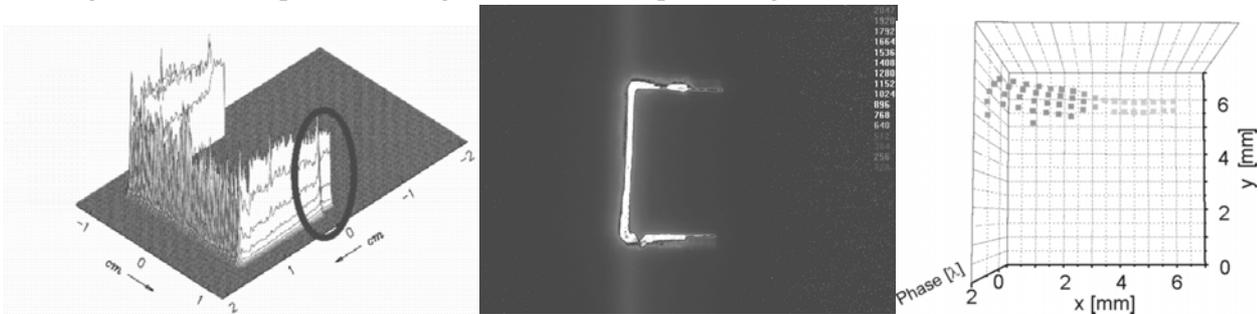


Fig. 10: Basic description of misaligned MNBUR, scraper misaligned against flow direction (distance from optical axis too small)

lower right part. These measured effects when misaligning the scraper are clearly predicted by numerical calculations. The corresponding 3-D plots are shown in the left part of figure 9 and figure 10, respectively, where the part of interest is marked by the oval. In addition, in both figures the data of the SHS are presented for the lower right part of the near field structure.

Insufficient alignment in vertical direction shows a comparable effect. The vertical scraper movement releases surplus radiation field in the opposite direction. As a consequence, the [-leg in moving direction displays a side wing. These experiences allow an exact resonator alignment by evaluating the contour of the produced beam. Due to the good agreement of calculated and measured results not only the directions but also the quantities of misalignment are well known from the structure of the measured contour plots.

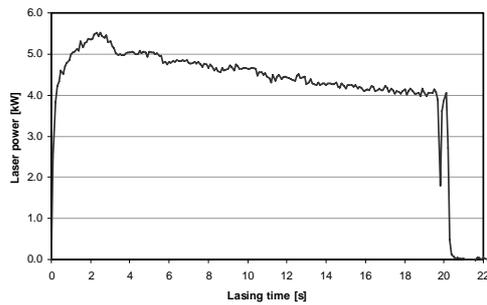


Fig. 11: Laser power extracted from MNBUR

In figure 11 the laser power coupled out of the MNBUR is plotted. The laser power achieves a maximum value of about 5.5 kW; the power decrease with time is due to the batch mode operation of the COIL-device with its rotating disk oxygen generator.

A maximum laser power of 5.8 kW was calculated taking into account the resonator layout data and the applied COIL geometry. That is, the experimentally achieved output power is very close to the maximum value.

As pointed out before, the MNBUR is a resonator designed for COIL systems of the 100 kW-class. Because of availability aspects it was tested at a 10 kW-class COIL in order to validate the results of numerical calculations for this resonator. Therefore, the magnification had to be very small making great demands on the accuracy concerning the curvature of the resonator mirrors. These demands could not be fulfilled perfectly by the manufacturer, turning out in a magnification of 1.04 instead of 1.05. In consequence, there is some reduction in the brightness of the emitted radiation. In order to compare theory and experimental results, detailed numerical calculations were carried out for the established resonator with the delivered mirrors.

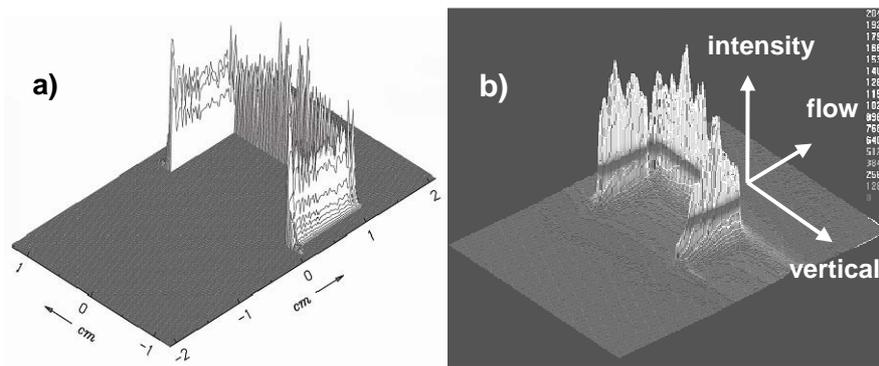


Fig.12: Comparison of calculated (a) and measured (b) near field intensity distribution

In figure 12 calculated and measured near field intensity distributions are compared. As already mentioned within the context of alignment, the measured beam size is in accordance with the theoretical prediction. Moreover, the intensity distributions are corresponding quite well although the substructures are differing to some extent. This is probably due to some non exact confocal arrangement and/or little deviations from the spherical form of the resonator mirrors.

Figure 13 presents a 2-D plot of the intensity distribution as measured in the focus of a lens. In addition, the numerical results for the set-up under consideration are presented as orthogonal scans. Size and even structure of the distribution are pretty much comparable. The frequency of the intensity modulation is as predicted, while the modulation depth is not quite as deep as expected. Again, this is probably due to some imperfectness of the resonator mirrors.

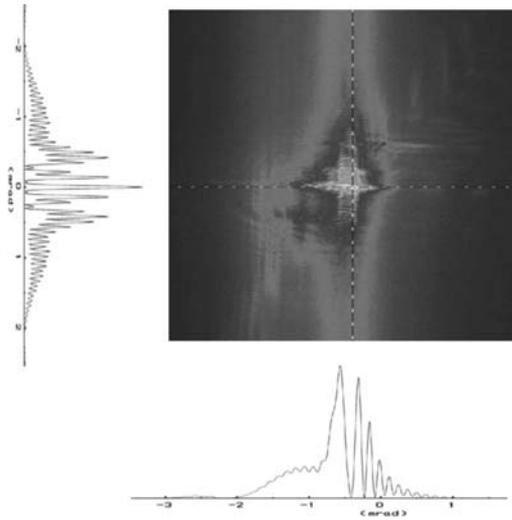


Fig. 13: Measured intensity distribution in the focus of a lens and numerical results

Because of the longer wavelength of a COIL in comparison with visible radiation and due to the small size of the CCD chip of the IR-camera the micro lens array of the SHS is only consisting of 20x16 elements. Therefore, the image of the near field intensity distribution is chosen to be larger than the CCD chip. For comparison of calculated and measured phase distribution as shown in figure 14, the different areas of the MNBUR output are recorded in succeeding laser operations and combined subsequently to the complete phase distribution. Another shortcoming of the phase measurement is the lack of a plane reference wave to acquire the reference grid. To overcome these difficulties the symmetry perpendicular to the flow direction is used during the evaluation of the measured data. The tilt in orthogonal direction had to be approximated according to the numerical results. Nevertheless, this method is very useful for a comparison of the obtained numerical and experimental data.

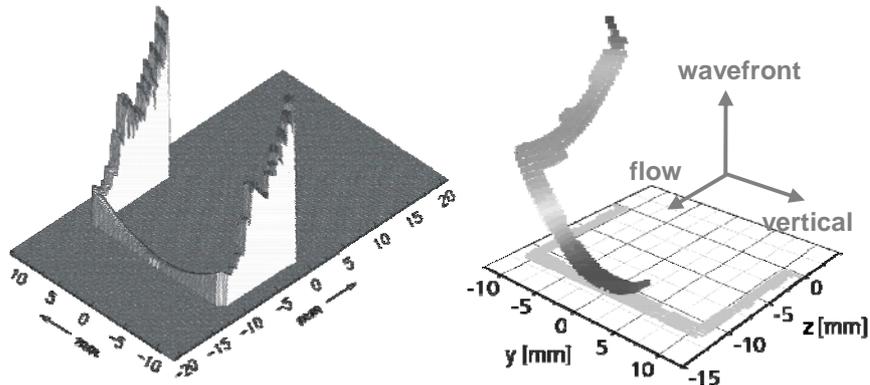


Fig. 14: Calculated (left) and measured (right) phase distribution of the near field

Obviously, the trends in phase deviation are very similar to each other. Both show a minimum at the center and the slopes of the curves coincide. The measurements exhibit a much less spatial resolution than the calculations and may be smoothed by some fluctuations in time.

V. Conclusion

The verification test of MNBUR is performed at an only medium-sized COIL with a very low magnification of 1.04. Despite of this restricting coupling condition, the MNBUR extracts nearly all achievable laser power. The alignment procedure is straightforward and the alignment quality is easy to control. Theoretical predictions and experimental results are in good agreement. The deviations of measured data from the calculation can be assigned to manufacturing imperfections, which are avoidable especially for higher magnification numbers. Since the theoretical treatment is proved to describe the actual resonator, a specific high brightness MNBUR can be reliably designed for an adequate power in a 100 kW-class COIL.

According to the realized magnification of only 1.04, detailed investigations concerning the beam quality are inappropriate. For this special purpose, an additional MNBUR will be designed for the DLR-COIL with a magnification close to the lasing threshold condition of the device.

Acknowledgments

The authors like to express their gratitude to Dr. Gerhard Spindler, whose good ideas, experience, and essential contributions to the discussions were a great support during the investigations and made a valuable contribution to this paper.

References

1. S.L. Druzhinen, A.V. Savin, S.Yu. Strakhof, "Unstable multi-pass resonator for ten-kW-class nitrogen-based supersonic COIL", XV Int. Symp. on Gas Flow, Chemical Lasers, and High-Power Lasers, (edited by J. Kodymová, Prague 2004), Proc. SPIE, **5777**, 135-141, Bellingham, WA, 2005.
2. A.H. Paxton, W. P. Latham, Jr., "Unstable resonators with 90° beam rotation", Appl. Opt., **25**(17), 2939-2946, 1986.
3. S. Holswade, R. Riviere, C.A. Huguley, Ch. M. Clayton, G.C. Dente, "Experimental evaluation of an unstable ring resonator with 90° beam rotation: HiQ experimental results", Appl. Opt., **27**(21), 4396-4406, 1988.
4. D. Yu, F. Sang, Y. Jin, Y. Sun, "Output beam analysis of an unstable resonator with a large Fresnel number for a chemical oxygen iodine laser", Journal of Optical Engineering, Vol. 41,(10), 2668-2674, 2002.
5. Y. Jin, B. Yang, F. Sang, D. Zhou, L. Duo, Q. Zhuang, " Experimental investigation of an unstable ring resonator with 90-deg beam rotation for a chemical oxygen laser", Appl. Opt., **38**(15), 3249-3252, 1999.
6. A.E. Siegman, "Unstable optical resonators for laser application", Proc.IEEE **53**, 277-287, 1965.
7. A.E. Siegman, "Unstable optical resonators", Appl. Opt. **13**, 353-367, 1974.
8. J. Handke, W.O. Schall, Th. Hall, F. Duschek, K.M. Gruenewald, "Chemical oxygen-iodine laser power generation with off-axis hybrid resonator", Appl. Opt., **45**(16), 3831-3838, 2006.
9. Th. Hall, F. Duschek, K.M. Gruenewald, J. Handke, "Modified Negative-Branch Confocal Unstable Resonator (MNBUR)", Appl. Opt., **45**, 8777-8780, 2006.
10. L.v. Entress-Fürsteneck, J. Handke, K. Grünwald, "Supersonic COIL operation at DLR, Germany", 11th GCL/HPL, SPIE, **3092**, 553 – 556, Edinburgh, 1996.
11. K.M. Grünwald, J. Handke, F. Duschek, "Small signal gain and temperature profiles in supersonic COIL", 13th GCL/HPL, SPIE, **4184**, pp. 75 - 78, Florence, 2000.
12. J.W.Goodman, "Introduction to Fourier Optics", McGraw-Hill, 1968.
13. A.G. Fox, T. Li, "Resonant Modes in a Maser Interferometer", Bell Syst.Techn. Journ., **40**, 453 ff, 1961.
14. Th. Hall, F. Duschek, K.M. Grünwald, J. Handke, W.O. Schall, "Numerical Studies on Hybrid Resonators for COIL" . XV Int. Symp. on Gas Flow, Chemical Lasers, and High-Power Lasers, (edited by J. Kodymová, Prague 2004), Proc. SPIE, **5777**, 131 - 134, Bellingham, WA, 2005.
15. Th. Hall, "Numerical studies on hybrid resonators for a medium-sized chemical oxygen iodine laser", Opt. Eng. **44**(11), 114201, 2005.
16. J. Handke, K.M. Grünwald, F. Duschek, "Comparative studies on small signal gain and output power for COIL systems", 13th GCL/HPL, SPIE, **4184**, 45 - 48, Florence, 2000.