HIGH-ACCURACY ALIGNMENT BASED ON ATMOSPHERICAL DISPERSION – TECHNOLOGICAL APPROACHES AND SOLUTIONS FOR THE DUAL-WAVELENGTH TRANSMITTER

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1. INTRODUCTION

In the course of the progressive developments of sophisticated geodetic systems utilizing electromagnetic waves in the visible or near IR-range a more detailed knowledge of the propagation medium and coevally solutions of atmospherically induced limitations will become important. An alignment system based on atmospherical dispersion, called a dispersometer, is a metrological solution to the atmospherically induced limitations in optical alignment and direction observations of high accuracy [1].

These atmosphere-related effects arise from density variations in the propagation medium, i.e. in the air, due to spatial and temporal variations in the atmospheric states, e.g. temperature and pressure. Thereof inhomogeneities in the refractive index field occur which lead to gradients in the refractive index of the air. So the detrimental influences of the ambient air are induced by the quasi-stationary gradients which appear to have a predominating systematic component. These refraction effects cause discrepancies in angle between the true and the apparent direction, which are called in geodetic context the refraction angles. As far as the complete description of the propagation medium is concerned a contribution towards atmospherical turbulence has to be made. Larger turbulence structures with a long-lasting influence can also cause similar effects, as described above. However, the stochastic influences of a turbulent atmosphere can be significantly reduced by extending integration time. Hence, the accuracy of optical direction measurements and direction transfers is not limited by the precision of the alignment systems but by these inhomogeneities in the atmosphere that cannot be averaged out within reasonable integration times [2].

In the dispersometer we are using the dual-wavelength method for dispersive air to obtain refraction compensated angle measurements, the detrimental impact of atmospheric turbulence notwithstanding. The principle of the dual-wavelength method utilizes atmospherical dispersion, i.e. the wavelength dependence of the refractive index. The difference angle between two light beams of different wavelengths, which is called the dispersion angle $\Delta\beta$, is to first approximation proportional to the refraction angle:

$$\beta_{IR} = \nu\,(\beta_{blue} - \beta_{IR}) = \nu\ \Delta\beta, \qquad (1)$$

herein arbitrary shown for the vertical refraction angle β_{IR} for the IR-radiation. Furthermore β_{blue} in equation (1) denotes the vertical refraction angle for blue light. Analogue results can be obtained for the calculation of the horizontal refraction angle. The wavelength dependent

constant ν, the reciprocal dispersive power, can be derived by using on laboratory measurements based interpolation formulae, e.g. the 1965-dispersion formula by Edlén [3]. The value of ν for the presently used wavelengths is ~42.
The initial quantities of observation, the dispersion angles in the horizontal and vertical direction appear as the horizontal and vertical displacement components on the semiconductor detection system in the focal plane of the dispersion telescope. With known focal length f of the telescope one can calculate, e.g. the vertical dispersion angle $\Delta\beta$. And thereof using equation (1) finally, e.g. the vertical refraction angle β_{IR} at the IR-wavelength can be obtained. A more detailed analysis can be found in [1].
Equation (1) implies that the dispersion angle has to be measured at least 42 times more accurate than the desired accuracy of the refraction angle for the wavelengths used in the present dispersometer. This required accuracy constitutes one major difficulty for the instrumental performance in applying the dispersion effect. However, the dual-wavelength method can only be successfully used in an optimized transmitter-receiver combination. Beyond the above mentioned resolution requirement for the detector, major difficulties in instrumental realization arise in the availability of a suitable dual-wavelength laser light source, laser light modulation with a very high extinction ratio and coaxial emittance of monomode radiation at both wavelengths. Therefore, this paper focuses on the solutions of the dual-wavelength transmitter introducing a new hardware approach and a complete re-design of the in [1] proposed conception of the dual-wavelength transmitter.

2. INSTRUMENTAL APPROACH FOR THE DISPERSOMETER

According to the dual-wavelength method the dispersometer consists of two modules: the dual-wavelength transmitter and the detector being composed of a dispersion telescope and a semiconductor detection system. Summarizing the instrumental approach for the alignment system based on atmospherical dispersion a short description of the complete system is given in this section.

2.1 The basic conceptions

One main focus of the instrumental realization is to develop a system with a monolithic structure. Both beams propagating from the laser light source to the detector should be rigorously affected by the same influences. This implies that both beams are guided strictly coaxial. Only the apparent utilized physical effect, i.e. atmospherical dispersion, displaces both beams. Furthermore, the proposed detection system is also one monolithic system. That means, with the exception of the wavelength dependent drifting and the wavelength dependent absorption depth on the photodiode, which have to be calibrated, all impacts will affect both signals. Another goal of the development is that a future integration into existing high-end theodolites is possible. The derived requirements prescribe detector optics with similar specifications than ordinary theodolite telescopes.

2.2 Dual-wavelength transmitter

In order to exploit the small effect of atmospherical dispersion one needs laser radiation at two different wavelengths, which are optimized in spectral separation according to the dual-wavelength method. Furthermore due to the detector concept and for the reduction of the

influence of background radiation the possibility of modulation with very high extinction ratio is required. Beyond this, the dual-wavelength transmitter has to generate a reference signal for synchronization and wavelengths demultiplexing at the receiver.
The observation method of the dispersometer is characterized by measuring the dispersion angle between the two beams. This is realized by detecting the centers of gravity of the imaged intensity distributions in the focal plane of the receiving telescope with the resolution capability given in sub-section 2.3. Therefore beams with specific symmetrical intensity distributions have to be generated. Furthermore, time depending interference effects within the beams have to be eliminated. As a consequence either a so called Gaussian $TEM_{0,0}$ beam for both wavelengths is required. To obtain the Gaussian beam quality with a smooth intensity distribution one uses in optical applications the techniques known as spatial filtering because in general the laser beam is a superposition of Gaussian-Hermite waves ($TEM_{p,q}$ with $p,q = 0, 1,...$). To achieve the desired Gaussian $TEM_{0,0}$ beam one has to eliminate all the $TEM_{p,q}$-waves with $p,q \neq 0$. In figure 1 the intensity distributions of low-order $TEM_{p,q}$-waves are depicted. The case $p = q = 0$ is the wanted case.

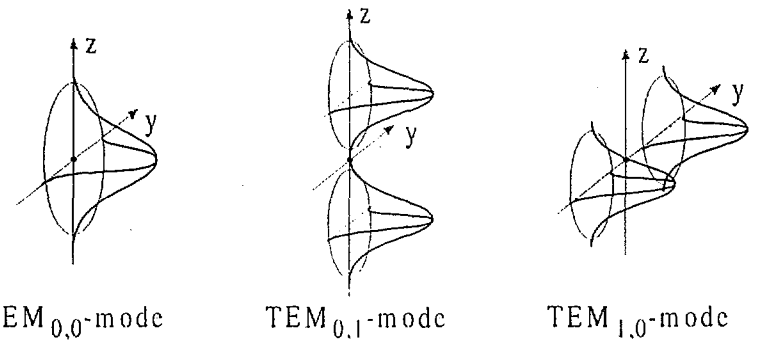

Figure 1: Intensity distribution of low-order $TEM_{p,q}$-modes for $p = q = 0$ and $p + q = 1$

With a dispersometer however, the situation is much more complicated, because at both present wavelengths a Gaussian $TEM_{0,0}$ beam has to be generated. The second important requirement is coaxiality of both beams with a coincidence <1 µm assuming the shortest system sight length of 30 m. Within this tolerance mutual angular stability has to be assured. We investigated as only existing technology on which the development can base the application of optical fiber technology. See sub-section 3.3 for details.
Once the required beam properties have been generated, getting in line with the receiver will be done by a pointing-theodolite. Therefore, the optical fiber will be coupled in one modified optical channel of a today's theodolite.

2.3 Conception of the receiver

After propagating through the atmosphere both beams are collected by an especially calculated dispersion telescope with a focal length of 300 mm, by a total assembly length including the semiconductor detection system of approximately 320 mm. Consequently, the demand of a telescope with a short focal length has been met. The maximum aperture of 75 mm can be reduced continuously for analyzing the functional dependence of the sensitivity of the turbulence compensation mechanism on the aperture size (see Fig. 2).

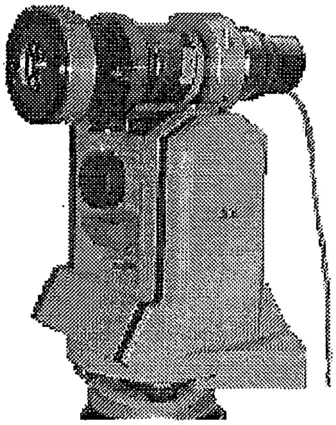

Figure 3: Dispersion telescope mounted on a LEICA TM3000D theodolite

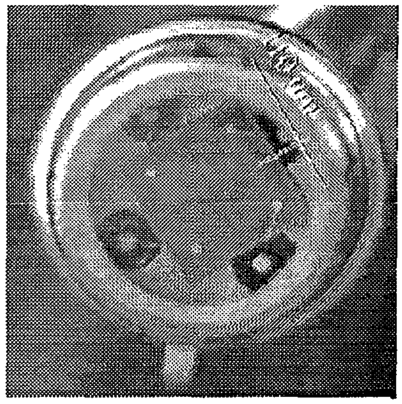

Figure 2: Quad-cell-PSD with gap area in between the sensitive areas

By the assumption of a refraction angle in the order of 1 µrad, related to the dual-wavelength theory, the magnitude of the wavelength dependent constant ν implies that the dispersion angle has to be resolved better than 0.03 µrad. This angular value is equivalent to resolution on the sensor of 10 nm with the consideration of a predetermined focal length of 300 mm of the optical system. Although the used types of position sensitive detector (PSD) are segmented photodiodes, either the dual- or the quad-cell type, the 110 µm wide gap, in between the actually sensitive areas, performing as a lateral detector is utilized (see Fig. 3).

3. TECHNOLOGICAL SOLUTIONS FOR THE DUAL-WAVELENGTH TRANSMITTER

To meet the specifications and requirements as given in section 2, a dual-wavelength transmitter with complete new hardware approach has been developed. A schematic overview of the dual-wavelength transmitter is given in figure 4 below.

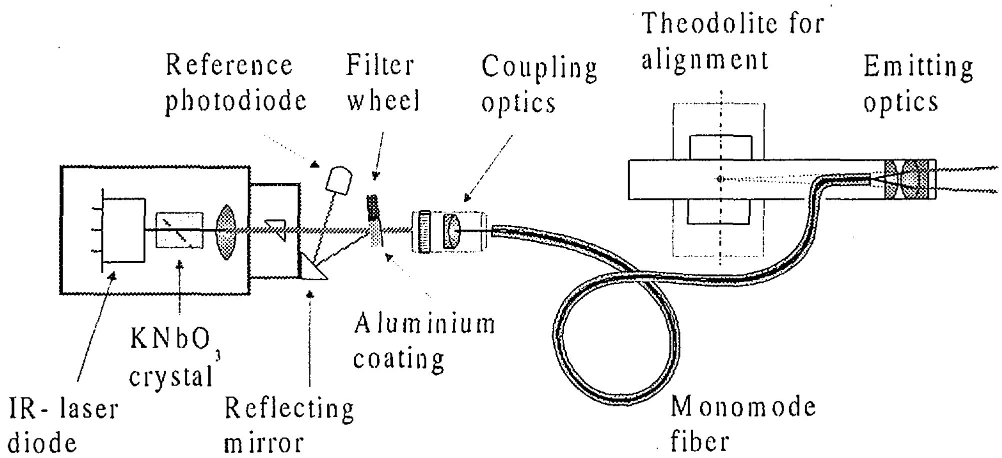

Figure 4: Schematic drawing of the dual-wavelength transmitter

3.1 Dual-wavelength laser source

The core of the dual-wavelength emitting unit (see Fig. 4) is the dual-wavelength laser generating blue light by frequency doubling of the wavelength of a semiconductor IR-laser diode in a bulky potassium niobate ($KNbO_3$)-crystal [4]. At the time being this type of all-solid-state laser is a superior alternative laser light source to the deep blue emitting diode lasers. Although the models of blue laser diodes are commercially available, however with no lifetime guarantee, it will take further considerable effort in research and development until these devices meet the standards of nowadays IR-laser diodes [5]. For the instrumental realization of a monolithic dual-wavelength transmitter a laser generating the second wavelength by frequency doubling is ideally suited and leaves out the problem of beam combining. Approximately 2.5 mW IR @860.5 nm and 2.2 mW blue light @430.25 nm are available at the output of the dual-wavelength laser. The wavelengths have been measured with an accuracy of 0.1 nm @860.5 nm. The output power was determined after passing the dichroic beam splitter which allows matching the IR-portion (maximum value 500 mW) to the blue light power level, which is necessary due to the efficiency of the second harmonic generation.

3.2 Intensity modulation and wavelengths demultiplexing

Due to the detection scheme it is required to send the beams alternately. The correlation of the two optical paths demands a separation rather in time than in space. Therefore, the modulator provides intensity modulation and wavelength selection as well. Wavelength selection is achieved by optical SCHOTT glasses BG39 and RG780. With a thickness of the filter glasses of 3.0 mm suppression of more than 10^5 (50 dB) results, which has been demonstrated using a PERKIN ELMER Lambda 9 spectrometer, so that evidently no crosstalk between blue light and IR occurs on the receiving detector. The filter wheel with constant angular speed generates a temporal intensity modulation with a frequency of ~250 Hz for each wavelength. Furthermore, the chopping frequency can be adjusted to the turbulent conditions. The periods when neither blue nor IR are transmitted, realized by a 150 nm thick aluminium coating evaporated on the backside of the filter wheel, are used in the detection scheme for background and offset measurements (see Fig. 5). Further specifications of the filter wheel are given in sub-section 3.3. For wavelengths demultiplexing and synchronization of emitting and receiving units a reference signal is extracted from the coaxial beams by a two mirror system, wherein the aforementioned aluminium coating depicts the first reflecting mirror. This reference signal is then transmitted to the receiver.

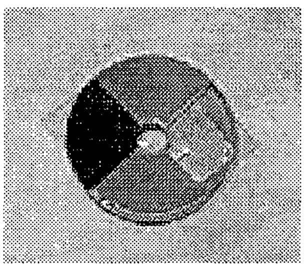

Figure 5: Filter wheel (dia. 15 mm) consisting of 3.0 mm thick BG39 and RG780 glass filters, two quadrants have been evaporated with a 150 nm thick aluminium coating. The filter wheel is laying on the evaporation mounting shortly after the evaporation process. The blank quadrants have been covered by gallium arsenide wafers to produce sharp edges.

3.3 Solution to coaxial dual-wavelength monomode propagation by the application of optical fiber technology

Although the dual-wavelength laser exhibits good beam quality, even this laser beam quality is not sufficient for the dispersometer (see Fig. 6a and 6b for details).

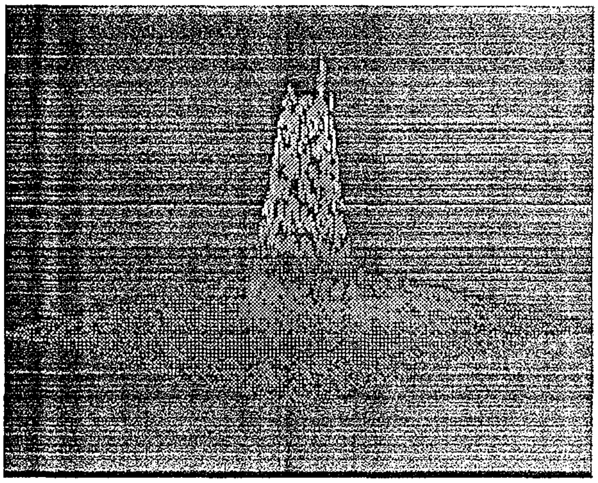

Figure 6a: Real laser beam profile @430 nm

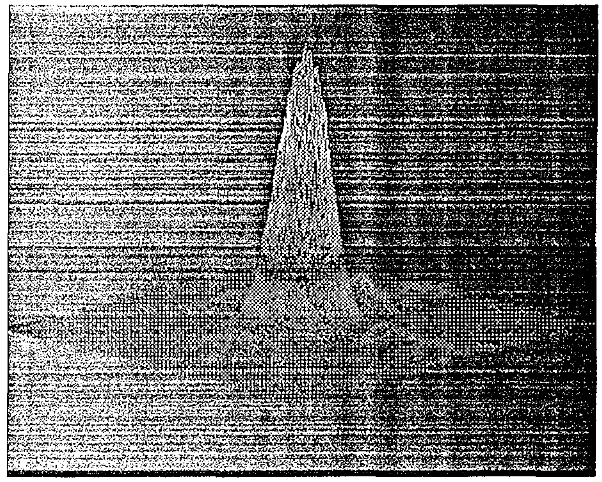

Figure 6b: Real laser beam profile @860 nm

To meet the requirements of coaxial dual-wavelength monomode propagation both beams have to be coupled into the same single-mode fiber. A mode is characterized as a time independent intensity distribution. A single-mode fiber is a cylindrical dielectric waveguide with a central core in which the light is guided. The core is embedded in an outer cladding with a typical 1% lower refractive index than the refractive index of the core. To first approximation the simple model of internal reflection at the core-cladding boundary can be applied. Hence rays with an incident angle smaller than the critical angle θ_c of total internal reflection are not guided and spread power into the cladding material (see Fig. 7).

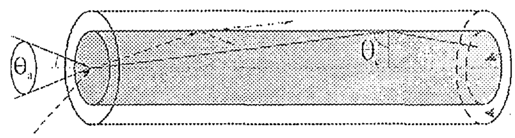

Figure 7: Single-mode fiber with the geometrical optics propagation model

Unlike this approximation, the exact theory shows merely different discrete modes propagating with different reflection angles. The angle of acceptance θ_a for the guiding of light is defined by the numerical aperture (NA) of the fiber. Because of the requirement of monomode propagation it has to be demonstrated experimentally that for both wavelengths only the fundamental mode is transmitted. For theoretical predictions of monochromasy and guidance behavior within the fiber the so called cut-off wavelength depending on the core diameter and refractive indices is used. For an operational wavelength far above the cut-off wavelength, as it is the case with the 860 nm wavelength, mode confinement becomes looser whereby bend sensitivity increases. Hence, for guiding both wavelengths within the same fiber certain trade-offs have to be made.
The typical parameters for the single-mode fibers used in the experiment are NA = 0.11 to 0.13, nominal core diameter 2.5 µm to 3.5 µm and the cladding diameter of 80 µm to 125 µm. The smallness of the core diameter implies very tight specifications for planity and parallelity of the

filter surfaces when a satisfying coupling efficiency should be achieved. Assuming a 7° deviation of the rotation axis of the filter wheel from the propagation direction, because of feedback suppression, the surfaces of the agglutinated filter wheel are specified to 1″ parallelity and $\lambda/10$ planity. Yet another viewpoint of light launching into fibers is the design of the coupling optics. Optimizing the parameters NA and spotsizes for both wavelengths, we achieved the best coupling efficiency with an achromatic well corrected 60X microscope objective.

Theoretically, the first important condition for single-mode operation for both wavelengths is that the cut-off wavelength has to be lower than the shorter wavelength. However, nowadays having the growing market of fiber optical technology, manufactures give the cut-off wavelength with large tolerances spanning several ten nanometers in wavelength. Secondly, the 430 nm wavelength generated by the frequency doubling is not a common wavelength, generated by commercially available laser sources. Fibers tailored to the Ar^+-lasers tend to have a higher cut-off wavelength than 420 nm which would be needed. Fibers for HeCd-lasers (442 nm) are not on the market. In the course of the development 18 different single-mode fibers have been tested concerning transmission, bend sensitivity and the exhibiting beam profiles have been analyzed. We have investigated experimentally, that for single-mode fibers which excite solely the fundamental mode @430 nm and @860 nm, the mode confinement @860 nm becomes so loose that almost the complete measurable IR-radiation is absorbed in the cladding material after approximately 100 mm of fiber length. Furthermore, the mode field of the IR-beam propagating will become so large that impurities of the cladding material will completely damage the profile beam. Another source of disturbance is that force centering of the fiber within the connectorizing process will partly induce birefringence which also has a detrimental effect on the beam profile. This latter mentioned source of errors could be eliminated using cleaved bare fibers in the function model.

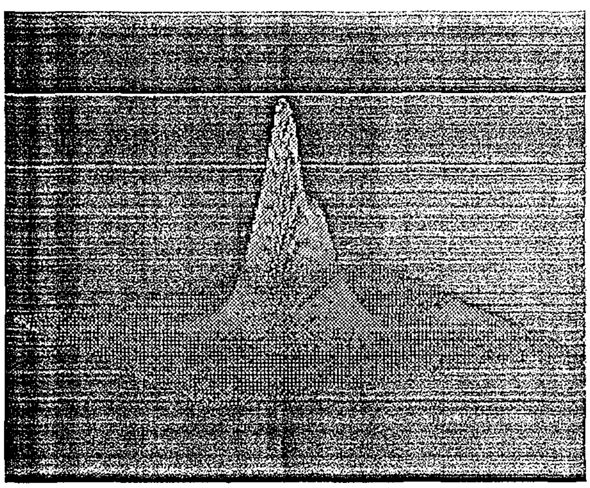

Figure 8a: Intensity profile of the fiber out-coupled beam @430 nm. The smaller peak acknowledges higher order mode content.

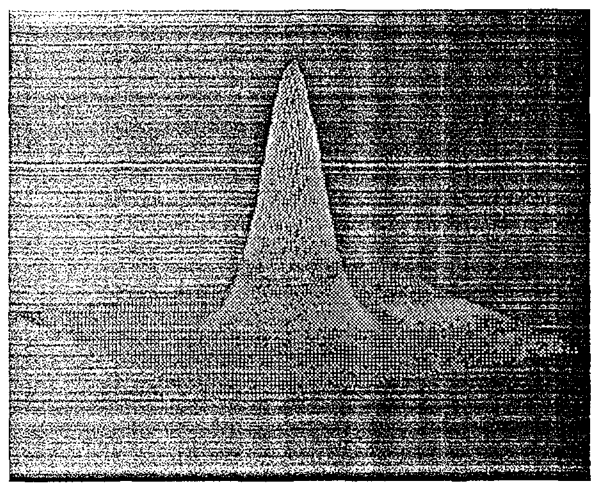

Figure 8b: Beam profile of the fiber out-coupled beam @430 nm. The beam is purged to single-mode propagation due to the applied technique.

For the solution of the monomode problem we have introduced a new method in the dual-wavelength emitting unit which is closely related to the geometrical propagation model. We have chosen an optical fiber which exhibits single-mode propagation @860 nm with a satisfying power transmission. For this type of fiber the cut-off wavelength is 448 nm, which indicates the possibility of co-excitement of the fundamental mode LP_{01} and the second-lowest order mode, the LP_{11}-mode. This fact has also been demonstrated experimentally. To purge the 430 nm wavelength to single-mode smooth mechanical manipulations have been introduced, so that a regime could be found where the LP_{11}-mode becomes leaky and solely the LP_{01}-mode corresponding to the fiber out-coupled free space Gaussian $TEM_{0,0}$ beam is guided. Figures 8a and b demonstrate the effectiveness of the applied technique.

3.4 Measurements of the beam profiles at both wavelengths

In order to verify the propagation of the fiber out-coupled Gaussian $TEM_{0,0}$ beams we recorded the far-field intensity distribution with a PULNIX TM-6 CCD-camera and processed the data using a SPIRICON LBA100A laser beam analyzing system. Utilizing the complete dynamic range of the CCD-camera we attenuated the transmitted power of the beams by lowering the coupling efficiency. Unlike using absorption filters the true beam profile remains.

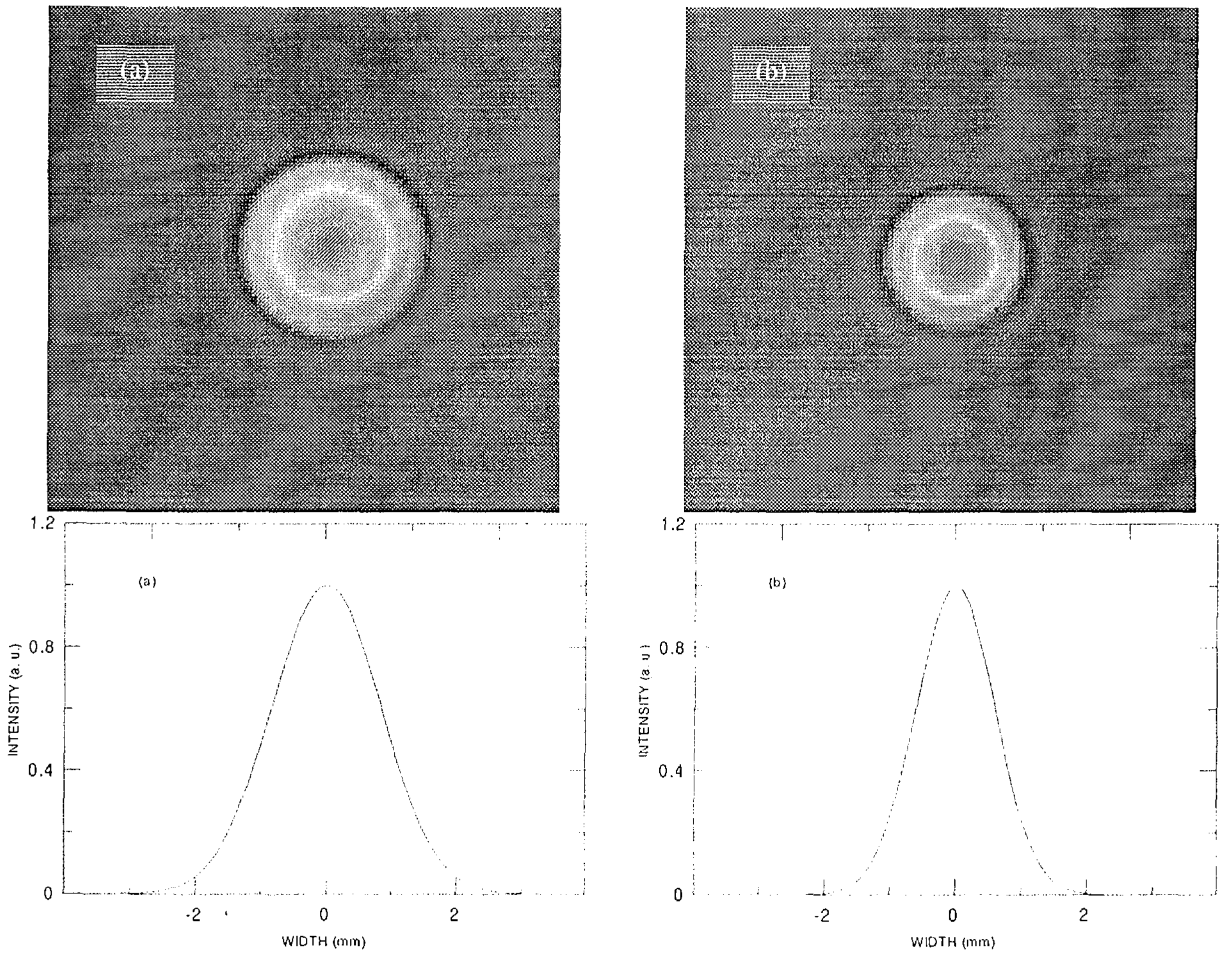

Figure 9: Recorded beam profiles @430 nm (a) and @860 nm (b). Both graphs show the appertaining intensity profile @430 nm (a) and @860 nm (b) calculated from the best Gaussian fits.

Changing the launching-in geometry by beam-steering with the microscope objective is favorable for this kind of analysis. Because the LP_{11}-mode is characterized as an asymmetrical mode it will be easier excited by a non-optimized asymmetrical coupling. This implies on the other hand, when single-mode propagation exhibits with *this* launching-in condition single-mode propagation will appear in *all* possible cases. Figures 9a and 9b show the recorded typical profiles of the fiber out-coupled beams for both wavelengths.
Calculating the ratio of the minor and major width of the $1/e^2$ intensity a roundness value of 0.99 for the 430 nm radiation (see Fig. 9a) and also a roundness value of 0.99 for the 860 nm radiation (see Fig. 9b) results. Both beam profiles show very good correlation with the theoretical Gaussian beam profiles. For the beam profile of the 430 nm wavelength a correlation of 0.93 for both the major axis and for the minor axis results. The beam profile at 860 nm exhibits a correlation of 0.96 for the major axis for the minor axis, respectively. These fittings acknowledge that solely the fundamental mode is guided and show the effectiveness of the applied technique for purging the 430 nm wavelength to single-mode propagation. Based on these measurements we assumed diffraction limited beam quality. Furthermore, we derived the far-field half angle divergence θ from a fit of the width of the $1/e^2$ intensity as a function of position along the direction of propagation. The far-field half angle divergence θ @860 nm is 3.8° and @430 nm $\theta = 5.1°$. From these values we derived the radii w_0 of the mode fields propagating within the fiber. The results are w_0@860 nm = 4.2 µm and w_0@430 nm = 1.6 µm. The magnitude of the latter beam waist is as expected for this wavelength. The beam waist @860 nm, which is a factor 2.6 larger acknowledges that a larger portion of IR is transmitted in the fiber cladding. As far as the excellent beam quality is concerned this should not lead to any limitations and is also in accordance with the theory of cylindrical waveguides. The present system emits typical 1 mW of optical power @430 nm and 0.5 mW of optical power @860 nm from the fiber output.

3.5 Transmitter optics

With the measurements and the determination of the half-angle divergences and the beam waists for both wavelengths the initial parameters for the design of the transmitter optics are given. Up to this stage of development the dual-wavelength transmitter is represented by the two beams coupled out of the optical fiber. Because of the magnitude of the resulting divergence angles, a large amount of optical power cannot be collected by the receiving optics. Hence, it is one issue for the beam shaping optics to reduce these divergence angles.
For simplifying the alignment procedure on the transmitter side the optical fiber is coupled into the optical system of a theodolite. The pointing of the dual-wavelength transmitter towards the receiving unit should tolerate an angular pointing deviation of 290.9 µrad (1'), i.e. 9 mm at the shortest system sight length of 30 m. For this pointing accuracy two basic requirements for the optical system have to be met. First, the virtual images of the fiber-output for both colors have to be produced in the same image plane. Second, this image plane has to be located in the tilting axis of the theodolite. If the first condition is not met an apparent dispersion angle would result on the detector. Infringing the second requirement, a systematic displacement occurs. Both effects are functions of the angular pointing deviation. If both conditions have been kept the origin of spherical wave propagation is identical for both wavelengths and rotation invariant. Furthermore, the additional advantage of robustness against mechanical vibration for the dual-wavelength transmitter occurs. For precipitating these aforementioned optical properties the

design of such an optical module and the modifications of an optical channel of a modern theodolite are currently under construction.

4. CONCLUSIONS AND OUTLOOK

We demonstrated with the recent set-up of the dual-wavelength transmitter dual-wavelength laser light generation, laser light modulation with a very high extinction ratio and stable coaxial monomode propagation at both wavelengths with sufficient optical power for field applications of the dispersometer system. At the present stage of development all requirements have been met. However, these results could solely be achieved by applying the most recent technologies in the fields of quantum electronics and modern optics as shown in this paper. The present layout of the dual-wavelength transmitter is shown in figure 10.

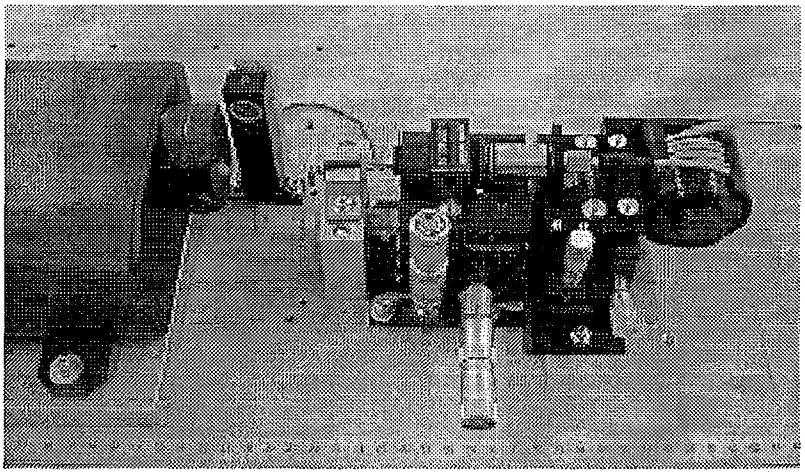

Figure 10: Realisation of the dual-wavelength transmitter

As far as an alignment system based on the dispersion effect can be regarded as system, the following developing stages will deal with the high-resolution sensor. However, only now with the dual-wavelength transmitter in the presented stage of development it will be possible to calibrate the detector thoroughly and conclusive.

According to the feasibility study of [2] reporting of an accuracy of the refraction compensated direction of 0.7 μrad with a sight length of 50 m, the high technological effort for a working dispersion based alignment system is justified, because at the moment neither an alternative metrological solution, nor the suitable modelling exist, to achieve optical alignment and observations of high accuracy in the ambient air.

5. REFERENCES

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