PROGRESS TOWARDS THE IMPLEMENTATION OF A BRILLOUIN-LIDAR FOR REMOTE SENSING OF THE TEMPERATURE PROFILE IN THE OCEAN

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ABSTRACT
Interaction between the atmosphere and the ocean takes place primarily in the upper ocean mixed layer. Therefore, knowledge of the temperature profile in this region is of particular interest, as it would provide valuable input to climate studies, weather forecasts and oceanography in general. Currently, those measurements are realized by in-situ techniques such as buoys, gliders and expandable bathythermographs. In order to provide an attractive alternative, a lidar method based on Brillouin scattering is currently in development. This remote sensing technique allows to deliver cost-effective on-line data covering an extended region of the ocean.

The Brillouin lidar we propose consists of two main components: The light source is a pulsed, three stage Yb-doped fiber amplifier with subsequent frequency doubling. The measurement of the Brillouin shift is performed by a spectrally highly resolving atomic edge-filter in the form of an excited state Faraday anomalous dispersion optical filter (ESFADOF). Both components are intrinsically insensitive to vibrations and exhibit low power consumption. Therefore, the system is perfectly suited for the operation from a mobile platform.

Using the fiber amplifier we have performed first range resolved measurements in our laboratory set-up. To determine the Brillouin shift, a scanning Fabry-Perot interferometer was used in these measurements. However, this setup is not capable of real-time measurements. Switching to our ESFADOF will provide this capability. Recently, we improved the transmission characteristics substantially, due to a modified design for the magnetic field. This will soon allow us to reach the next milestone in the development of the Brillouin lidar: the successful interplay of the ESFADOF with the fiber amplifier under laboratory conditions.

1 INTRODUCTION
Modeling transport phenomena in the ocean and exchange processes between atmosphere and ocean require the input of large sets of data. One such parameter is the temperature profile of the mixed layer in the ocean. Currently, the ocean surface temperature is monitored by satellites, and the profile is extracted by the use of expandable bathythermographs, buoys or gliders. A system close to real time observation is highly desirable. One such remote sensing system could be a Brillouin lidar. It was proposed by Guagliardo et al. in 1980 (1) and due to the research of Fry and coworkers the practicability of this approach has been demonstrated in a laboratory environment (2,3,4).

The working principle of a Brillouin lidar is as follows: Short laser pulses are sent into the ocean. They undergo spontaneous Brillouin scattering on moving density fluctuations in the water. The backscattered light contains blue and red shifted frequency components with respect to the incident light due to the Doppler effect. Therefore, the shift of the Brillouin lines is sensitive to the local speed of sound. As the dependency of the sound velocity on the temperature is known, the water temperature information can be extracted from the measured Brillouin shift (5). In case of backscattered light under an angle of 180°, the relation between the Brillouin shift $\nu_B$ and the sound velocity $v_s$ is given by
\[ v_b = \pm 2 \frac{n(S, T, \lambda) \cdot v_s(S, T)}{\lambda} \]  

(1)

The refractive index \( n(S, T, \lambda) \) and the sound velocity \( v_s(S, T) \) depend on the salinity, the temperature and the wavelength \( \lambda \). Both dependencies are well-known (6,7,8). In principle, there is also a dependency on pressure, but this is straightforward and can be dropped for the present discussion. Concerning the salinity \( S \), historical data can be used. Therefore, the measurement of the Brillouin shift \( v_b \) allows to deduce the water temperature \( T \).

At our intended working wavelength of 543.3 nm, the expected frequency shift varies between ±6.8...7.8 GHz for water temperatures between 0 and 40°C. By analyzing the arrival time and the frequency shift, one can obtain depth and temperature information in a single-shot measurement. The employment of 10 ns long laser pulses yields a spatial resolution of approximately 1 m. At the same time, it allows a spectral bandwidth of approximately 45 MHz, when working at the Fourier-limit. This is highly desirable in order to resolve the frequency shift to the desired accuracy of 1-4 MHz which results in a maximum temperature accuracy of approximately 0.2°C (6).

In general, Brillouin scattering can be generated with laser light at any wavelength. In order to decide on a specific wavelength, one has to consider three main aspects: (i) the absorption coefficient of water, (ii) the availability of intense laser pulses, and (iii) the capability of the desired detection system. The absorption coefficient of water has its minimum in the blue spectral range (9). Therefore, the highest penetration depths can be obtained in that range. We decided to work in the green spectral range, where sufficiently intense laser pulses can be generated by second harmonic generation of an Yb-doped fiber amplifier. Its emission wavelength can be tuned to 543.3 nm, allowing access to the 5P_{3/2} → 8D_{5/2} transition in Rubidium (Rb). This transition allows to setup an ESFADOF edge filter for the frequency-resolved detection of the Brillouin scattering. Compared to blue light, the absorption coefficient in the green spectral range is up to one order of magnitude higher, depending on the chlorophyll concentration (10). Nevertheless, penetration depths of up to 100 m will be feasible (5).

2 THE LASER SOURCE

The desired measurement accuracy stated above and the necessity to mount the completed Brillouin lidar on a small helicopter or plane, place certain demands on the laser source. The main requirements are (i) emission wavelength 543.3 nm, (ii) a pulse length 10 ns, (iii) a pulse energy up to 1 mJ, (iv) repetition rate in the kHz range, (v) Fourier-limited bandwidth, (vi) high stability in a vibrationally challenging environment, (vii) compact dimensions, (viii) low weight, and (ix) economic power consumption. In order to meet these demands, we opted for the development of a pulsed Yb-doped fiber amplifier with subsequent frequency doubling. Our current setup has been described in detail in our previous EARSeL Workshop conference papers (11,12) as well as in other publications (13). Hence, we will only give a brief summary of its characteristics and performance. Using Ytterbium as the dopant provides a broad amplification spectrum, ranging from 1030 to 1100 nm. Therefore, after second harmonic generation, the green spectral range is accessible from 515 to 550 nm. Up to now, the fiber amplifier has been operated and characterized at a fundamental wavelength of 1064 nm, due to the broad commercial availability of the optical components. In order to combine the fiber amplifier with the ESFADOF, we will switch to 1086.6 nm shortly.

The spectral and temporal characteristics of the amplified laser radiation are defined by the seed source. Currently, we employ an external cavity diode laser (ECDL), due to its high power, small bandwidth and easy tunability. In the final configuration, it will be replaced by a distributed feedback (DFB) diode, as it intrinsically provides a higher wavelength stability. By means of an electro-optic modulator (EOM), 10 ns pulses are extracted from the continuous wave seed radiation with a repetition rate of up to 5 kHz. The temporal pulse shape is near Gaussian and ensures a spectral bandwidth close to the Fourier-limit after amplification.

The low energy seed pulses (330 pJ) are amplified in three consecutive Yb-doped fibers. Each fiber is pumped at a wavelength of 976 nm by fiber-coupled laser diodes. Due to the increasing peak power, the fiber core diameter is enlarged with each stage. The output power of the second
and third stage is limited by a nonlinear effect within the fibers - stimulated Brillouin scattering (SBS). Its onset is promoted both by the pulses' high peak power and narrow bandwidth. We constantly operate the amplifier below the SBS threshold in order to maintain a stable output energy and to protect the fibers from facet damages. The detection of the threshold occurs in real-time by analyzing the backscattered light from within the fibers with an avalanche photodiode.

Infrared pulses with a maximum energy of 516 µJ have been generated after the third amplifier stage. The overall amplification amounts to 61.9 dB. Frequency doubling occurs during single-pass-conversion in a nonlinear KTP crystal and shortens the pulse length to 7.1 ns. We achieve a conversion efficiency of 26.9%, arriving at green laser pulses with an energy of up to 131 µJ. Currently, we investigate the performance of a photonic crystal fiber (PCF) in the third amplification stage. In spite of their large core diameter, PCFs can be operated single-mode and polarization-maintaining, which is highly advantageous regarding the subsequent SHG process.

3 FIRST RANGE RESOLVED MEASUREMENTS

In order to demonstrate the feasibility of the detection principle in general and of the fiber amplifier in particular, we have performed the first range-resolved water temperature measurements based on the detection of Brillouin scattering (14). Therefore, we set up a "test-ocean" in our laboratory. It consists of two successive, horizontal tubes with a length of 1.8 m each and a diameter of 10 cm. Both tubes are filled with double-distilled water with zero salinity. The water temperatures can be controlled independently, ranging from 4 to 38°C. Optical access is given by the glass facets, which are mounted under an angle of 3° in order to minimize disturbing reflections. Green laser pulses of the fiber amplifier are sent through the tubes on-axis. The back scattered light is collected under a small angle by means of a D-shaped mirror and guided through a two-lens-telescope to a scanning Fabry-Perot interferometer (FPI). The transmitted light is detected by a photomultiplier tube (PMT) and finally, the electronic signal is gated by a boxcar integrator.

The achievable temperature accuracy greatly depends on the precise alignment of the FPI. Therefore, prior to the measurements, the etalons free spectral range was calibrated to 20.076 GHz ±1 MHz, enabling us to record the entire Brillouin spectrum with high precision. In order to determine the spectrum in a certain water depth, the delay of the boxcar integrator was adjusted correspondingly. Range-resolved measurements were performed by stabilizing the water temperature in the tubes to 32.4 and 4.6°C, respectively. The fiber amplifier delivered pulses at 532 nm with an energy of 36.9 µJ at a repetition rate of 5 kHz. The delay of the boxcar integrator was increased in nine discrete steps, defining nine independent measuring depths within the tubes. From each recorded spectrum the frequency shift of the Brillouin scattering was extracted and, by means of Eq. (1), the corresponding water temperatures were derived. Fig. 1 shows the resulting temperatures as a function of the water depth (solid line) together with the actual water temperatures (dashed line) as measured by thermocouples lowered into the water. Clearly, the data reproduce the two different temperatures with high accuracy. The plot reveals a spatial resolution of 1.5 m, which is due to the optical pulse duration and the finite gate size of the boxcar integrator.

Clearly, the described setup is not capable of delivering single-shot profiling. Furthermore, it lacks intrinsic stability against vibrationally challenging environments. Both of these drawbacks can be overcome by the ESFADOF detector, which is introduced in the next section. Due to recent progress, the ESFADOF will replace the FPI as the detector in a similar proof-of-concept experiment in the near future.
Figure 1: (a) Schematic of the two-part water tube system. Each segment can be stabilized to a different water temperature. The water flow directions are indicated. Laser pulses from the fiber amplifier are sent into the water from the left and hit a beam dump at the right. (b) Measured temperature distribution of the two segments stabilized at two different temperatures. The temperatures shown are measured with Brillouin scattering (solid line) and with a thermocouple (dashed line). The temperature step is clearly visible. Its broadening of about 1.5 m is due to the pulse duration and the gate length of the employed boxcar integrator.

4 THE DETECTOR

4.1 General Remarks

Our approach to measure the Brillouin shift in the final lidar system aims at the realization of a robust, customized, static edge-filter. The idea is to overlap the filters steep transmission edges with the backscattered Brillouin frequency components. It will allow to convert small frequency shifts into large changes of the transmitted intensity. Thus, by simple transmission measurement the determination of the water temperature is possible on an absolute scale with high precision. Best edge filter performance is ensured when meeting the following requirements: (i) Steep transmission edges, (ii) symmetrically located ±6.8...7.8 GHz around the working wavelength, (iii) providing a high overall transmission. In order to realize these characteristics, we focus on the concept of a FADOF (Faraday anomalous dispersion optical filter).

Briefly speaking, a FADOF consists of an atomic vapor cell, which is exposed to a strong homogeneous magnetic field and placed between two crossed polarizers. Its working principle is as follows (cf. fig. 2): The incident light is polarized by the first polarizer and then guided through the vapor cell, which must be traversed parallel to the magnetic field lines. Due to the Zeeman splitting in the magnetic field, the dispersion for left- and right-circularly polarized light becomes different in the vicinity of the absorption line. The light undergoes a highly frequency dependent rotation of its polarization. Finally, this rotation is converted to a frequency-dependent intensity by the second polarizer, which is rotated by 90° with respect to the first one. As a result, steep edges arise in the transmission spectrum as desired. In contrast to interferometric devices, a FADOF is operated without the necessity of any resonant techniques and provides excellent rejection of daylight due to the crossed polarizers.
Figure 2: Principle setup of our ESFADOF. A Rubidium cell (blue) is placed between crossed polarizers and penetrated by a strong longitudinal magnetic field (yellow arrows). The incident light (green) is linearly polarized (green arrows) and guided through the Rubidium cell. The pump laser (red) is injected by means of a dielectric mirror and populates the lower state of the ESFADOF transition. While traversing the cell, the polarization of the incident light is rotated. This is due to the different dispersions of the left- and right circularly polarized light (dark arrows) in the vicinity of the ESFADOF atomic transition. The state of polarization is transformed into an intensity after passing the second polarizer.

In case the working transition connects two excited states, one speaks of an excited state FADOF (ESFADOF). This is the case for our Brillouin lidar, since we make use of the $5\text{P}_{3/2} \rightarrow 8\text{D}_{5/2}$ transition in Rubidium at a wavelength of 543.3 nm. In order to populate the lower excited state, the Rb vapor is pumped via the $5\text{S}_{1/2} \rightarrow 5\text{P}_{3/2}$ ground-state transition at a wavelength of 780.24 nm. Furthermore, the vapor density is adjusted by the cells temperature reaching up to 200°C.

In the following, we will elaborate on the generation of the magnetic field and our latest results. Regarding the underlying basic theory of an ESFADOF, we refer to our earlier publications (15,16,17,18).

4.2 The magnetic field

The strong magnetic field turns out to be the most critical of all operating parameters of the ESFADOF. Its precise control is crucial as it defines the exact position of the edges. With increasing strength, the transmission edges are shifted further apart. In case of the Rb ESFADOF at 543.3 nm, a magnetic field of more than 0.6 T is needed to separate the transmission edges by the required 16 GHz. Maximum steepness of the edges can only be ensured in case of best possible homogeneity of the field. Otherwise, the edges are washed out and broadened. Providing such magnetic field in the Tesla regime homogeneously over a typical cell length of 30 mm is a challenging task.

We decided to develop a customized magnetic field system made from strong permanent magnets. Since the early 1980’s, there has been great advance in the field of permanent magnetic materials. Most prominently rare earth magnets were introduced and became commercially available. However, independent of their composition permanent magnets create inhomogeneous fields, when being used stand-alone. This issue can be overcome due to the research of Klaus Halbach. In 1980, he proposed an innovative arrangement of permanent magnets in order to create well-defined field geometries (19), now known as Halbach cylinders. The main idea is to arrange permanent magnets in the form of a cylinder, while directing their magnetization in well-defined directions. He found that this results in an intense field within the cylinders free inner space. Ideally, the field in the outer surrounding vanishes entirely. Among various types of fields, Halbach cylinders allow to generate a homogeneous dipole field within the ring. In order to provide the necessary magnetic field for the ESFADOF detector, we constructed a modified Halbach cylinder and mounted an oven, which contains the Rb cell, in its center.
Figure 3: (a) Cross-section of our modified Halbach cylinder. It consists of two horseshoe magnets, each of them composed of five strong NdFeB magnets (grey) and iron workpieces (yellow). The individual magnetization directions of the magnets are depicted by the white arrows. By arranging the half cylinders in a repulsive configuration, an intense and homogeneous field (indicated by the red arrows) is generated in the middle, where the Rb cell (blue) is located. Optical access is allowed by the gap between the two sections. (b) Measurement of the magnetic field along the Rb cells axis within our custom Halbach cylinder. The dark line is a simulated curve, computed with the electro-magnetic solver CST EM Studio 2010. Within the 30 mm long cell, a mean magnetic field of 608 mT is generated, with a maximum deviation of only ±1.1%.

Due to their wide commercial availability and low cost, we use standardized rare earth magnets. Specifically, we employ block-shaped Neodymium Iron Boron (NdFeB) magnets with dimensions of 60x60x30 mm³ and with a remanence of approximately 1.35 T. The magnetization axis points along their short side. Special care must be taken in order not to exceed their maximum operating temperature of 80°C. Since the Rb cell needs to be heated to up to 200°C, the magnets have to be cooled or the cell must be well isolated from its surroundings.

The vapor cell is made from fused silica and filled with Rb in its natural isotopic abundance. Its form is cylindrical with a diameter of 10 mm and an inner length of 30 mm. The glass facets are wedged and mounted under an angle of 11° in order to minimize etalon effects. The total length amounts to 39 mm. By means of a heating spiral, which is wound around the cell, and a Pt100 thermal sensor, which is in direct contact with the Rb cell, the cells temperature is controlled and stabilized. In order to reduce the radiated heat, the oven case is built from well-isolating polyether ether ketone (PEEK).

Fig 3(a) shows a cross-section of our magnet setup. We constructed two identical half cylinders, consisting of five NdFeB magnets each. In fact, the two arrays resemble horseshoe magnets, whose poles are arranged such that the magnets repel each other. By approaching them close enough, a sufficiently strong and homogeneous magnetic field is generated in the middle, while optical access is possible through the remaining gap of 11.6 mm. The free space between the magnets of each cylinder is filled with iron work pieces. They guide the magnetic flux of the NdFeB magnets very efficiently and thereby partly compensate for the missing magnets in these spots.

In order to verify the strength and homogeneity of the generated field, we measured the B-field with a Hall effect sensor of a Tesla meter (F.W. Bell 5080). Due to the sensors active diameter of 0.4 mm and the Tesla meters accuracy of 1 mT, the characteristics of the field profile were precisely resolved. Fig. 3(b) shows the obtained field profile compared to a simulation, which was calculated prior to the construction with the electro-magnetic solver CST EM Studio 2010 (20). Both agree very well. The systematic deviation of approximately 5% is possibly caused by slightly varying magnetic properties of the individual magnets. For the employment of the magnetic system within the ESFADOF detector, the mean magnetic field is the most important quantity. Within the 30 mm region of the Rb cell, it amounts to 608 mT, with a maximum deviation of ±1.1% only. Slightly larger cell dimensions are possible without sacrificing the homogeneity of the field. With this magnetic field configuration and cell we have performed transmission measurements of the ESFADOF setup in order to characterize the ensuing edge filter.
4.3 Current status of the ESFADOF

The experimental setup we use to record the ESFADOF transmission spectrum has been described elsewhere (21). Its main components and beams are depicted in fig. 4(a). The key component is a scanning ECDL at a central wavelength of 1086.6 nm. Due to an ECDL locking technique developed in our group (22), a mode-hop free tuning range of more than 30 GHz is accessible. After amplification and frequency doubling of the radiation, we can access a mode-hop free tuning range of more than 60 GHz around our selected ESFADOF transition at 543.3 nm. Typically, the Rb cell is probed with an optical power of 100 µW to record the ESFADOF spectra.

The pump radiation at 780.24 nm is provided by a seeded tapered amplifier, which provides a maximum power of 2 W. In order to pump the Rb cell as homogeneous as possible, the pump radiation is split into two beams and injected into the cell simultaneously from both sides. Within the Rb cell, the beams of the pump and the probe laser are carefully overlapped and focused to 230 µm and 200 µm, respectively.

Fig. 4(b) presents the ESFADOF transmission spectrum employing our magnetic field setup. The actual pump power amounted to \( P_{\text{Pump}} = 31 \text{ mW} \) for each of the two counter-propagating beams and the pump wavelength was detuned by \( \Delta \nu_{\text{Pump}} = -4 \text{ GHz} \) with respect to the \( 5S_{1/2} \rightarrow 5P_{3/2} \) transition without a magnetic field. The temperature of the Rb cell was adjusted to \( T_{\text{cell}} = 119^\circ \text{C} \). The plot shows raw data, recorded during a single 30 GHz sweep of the probe laser frequency. During the scan period of 2.5 s, 35,000 data points were accumulated. Other than a normalization and frequency calibration no further data processing or averaging has been performed. Apparently, the resulting curve does not reveal any visible noise on the scale shown. In fact, the noise amplitude amounts to 0.0002 only. The central frequency of 0 GHz corresponds to the field-free \( 5P_{3/2} \rightarrow 8D_{5/2} \) transition frequency.

Evaluating the transmission characteristics in detail reveals the following insights:

i. The spectrum consists of two narrow, widely separated transmission windows. The red-shifted maximum is located at \(-7.28 \text{ GHz}\) with a maximum transmission of 57.7%, while the blue-shifted peak transmits 47.9% at 7.56 GHz. The full width at half maximum (FWHM) of the peaks amounts to 1.56 GHz and 1.61 GHz, respectively. Since the Brillouin peaks' lin-
The spectrum shows an overall good symmetry, especially with regard to the inner transmission edges, which are most relevant. They differ only by a constant factor, which nearly equals the ratio of the maximum transmissions. At higher frequencies, both transmission windows show oscillatory structures, before dropping to vanishing transmission beyond ±15 GHz. The structure is more pronounced in the blue-shifted case. But since the structure occurs in a frequency range, which is irrelevant for the detection of Brillouin scattering, they can be disregarded. Currently, we investigate an optimization of the pump process at 780.24 nm. We intend to imprint different frequency detunings and opposed circular polarizations on the two counter-propagating pump beams. The idea is to populate the relevant hyperfine levels of the lower ESFADOF state $5P_{3/2}$ more efficiently. This possibly allows us to fully symmetrize the transmission edges. Furthermore, it might increase the plasma threshold (cf. v.) and thereby allow even higher ESFADOF transmissions.

The frequency ranges, in which the Brillouin peaks’ maxima for water temperatures between 0°C and 40°C occur, is shaded grey in the figure. Apparently, the edge separation is not yet sufficient, as the specified ranges are not fully located on the inner edges. In its current state, the filter would not provide a monotonously increasing transmission signal with rising water temperature. Of course, we intend to further increase the edge separation in order to overlap the Brillouin scattering with the inner transmission edges. Assuming that the shift of the transmission peaks grows linearly with the magnetic field, one can calculate the required additional field for optimal edge separation. We determined that maximum signal contrast is obtained, when the current transmission peaks are separated by an additional GHz. This corresponds to an extra magnetic field of 40 mT, which is rather marginal compared to the current overall field of 608 mT. We currently implement this this advance by mounting additional magnets around the cell oven. These magnets can be adjusted spatially in order to access a continuous range of extra magnetic fields. This will allow us to fine tune the edge separation and to ensure optimal filter characteristics.

In the center of the spectrum, at a relative frequency of 0 GHz, the transmission is reduced to 5.8%. One might argue that elastic Rayleigh scattering, which occurs at this frequency, is not sufficiently suppressed by the filter and may lead to false temperature measurements. Solving this issue is straight-forward and can be simply accomplished by adequately pre-filtering of the scattered light. Prior to analyzing it with the edge filter, it must be guided through another Rb cell that is also pumped, but not exposed to a magnetic field. The absorption spectrum of this cell provides a narrow absorption peak on the $5P_{3/2} \rightarrow 8D_{5/2}$ transition, corresponding to 0 GHz. Since the Rayleigh scattering is in resonance with this transition, it will be efficiently absorbed, while the Brillouin scattering is transmitted unattenuated. Thus, the only light reaching the actual ESFADOF edge filter are the Brillouin scattering contributions.

A further increase of either the cell temperature or the pump power leads to a breakdown of the transmission spectrum, leaving only a few percent of maximum transmission. This is due to the ignition of a laser-induced plasma within the Rb cell. We will report on the analysis of this effect in detail in our upcoming publications (23,24).
Figure 5: Simulation of the expected ESFADOF filter characteristic within the relevant temperature regime between 0 and 40°C. The solid line resulted from the evaluation of our current spectrum, shown in fig. 4(b). An unambiguous measurement of the water temperature is only possible between 0 to 20°C. When evaluating a modified version of the current spectrum, in which the edge separation is increased by an additional GHz, the dashed line is obtained. In this case, the complete temperature range is covered. The transmission of the Brillouin scattering increases strictly monotonously from 0.23 to 0.34. This corresponds to a relative increase of nearly 50%.

As pointed out, the ESFADOF will be suited to measure temperatures as soon as the magnetic field is increased by 40 mT. In order to simulate the expected filter characteristic, we modified the data that were recorded for the current spectrum (fig. 4(b)): The red- [-15 GHz; 0 GHz] and the blue-shifted [0 GHz; +15 GHz] range of the spectrum were shifted by -0.5 GHz and +0.5 GHz respectively. This combines to a 1 GHz increase of the edge separation. Both the original and the modified spectrum were convoluted with simulated Brillouin scattering spectra corresponding to temperatures between 0 and 40°C including the effect of temperature dependent linewidths. Fig. 5 shows the resulting filter characteristics. A normalized signal of 1 corresponds to full transmission of both the red- and the blue-shifted Brillouin-peak. With the current ESFADOF, an unambiguous measurement of the water temperature is only possible between 0 to 20°C. In case of the modified spectrum with optimized edge separation, the complete temperature regime is covered. Within this range, the transmission increases from 0.23 to 0.34 which corresponds to a relative growth of nearly 50%. Clearly, a strictly monotonic increasing transmission signal is obtained, which represents the intended ESFADOF filter characteristic.

5 OUTLOOK

At the moment we are in the preparation for validating the simulation result (cf. fig. 5) experimentally. Therefore, we combine the fiber amplifier, the test ocean and the ESFADOF into a single measurement unit. The fiber amplifiers wavelength is shifted to 1086.6 nm. After second harmonic generation, Brillouin scattering can be generated at the ESFADOFs working wavelength of 543.3 nm. In order to filter out disturbing Rayleigh scattering as mentioned above, we will utilize our current 30 mm Rb cell and pump it with another seeded tapered amplifier.

Additionally, we make further efforts to improve the characteristics of the ESFADOF filter. Therefore we have optimized the cell oven design which allows to employ a 40 mm long Rb cell within the magnetic field system in future setups. In combination with the improved pump process (see sect. 4.3ii), we expect to further increase both the height and steepness of the ESFADOF transmission edges. The exact locations of the edges will be adjusted by additional magnets as stated above.

We will also thoroughly examine the stability of the transmission spectrum, as it directly determines the achievable temperature accuracy. Fluctuations of the transmission spectrum can be caused by
variations of three experimental parameters: the pump power $P_{\text{Pump}}$, the pump frequency $\nu_{\text{Pump}}$ and the temperature of the Rb gas $T_{\text{cell}}$. Special care will be taken to lock each of these parameters to its optimal value by means of a closed loop. The achievable absolute accuracies amount to $\Delta P_{\text{Pump}} < 0.5$ mW, $\Delta \nu_{\text{Pump}} < 20$ MHz and $\Delta T_{\text{cell}} < 0.05$°C.

6 CONCLUSIONS

We have presented our progress towards a practical implementation of our Brillouin lidar to remotely measure the temperature profile of the ocean. Concerning the transmitter, our fiber amplifier setup generates up to 131 $\mu$J 7-ns pulses at 532 nm. Employing this setup we have demonstrated depth resolved measurements employing a slowly scanning Fabry-Perot interferometer and a gated integrator. Although successful as a proof-of-principle, this setup is not yet capable of real time measurements of temperature profiles. To this end we are developing an ESFADOF based edge filter which will replace the interferometer. It allows to transform the small Brillouin shifts into large changes in transmission which can be detected with high precision. Employing a modified Halbach cylinder we were able to produce homogenous magnetic fields with the required strength. Transmissions up to 57.7% are feasible. The next steps will be to complete the ESFADOF setup and to employ it in the first real time measurements of the temperature profile.

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REFERENCES


