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# Rapid-prototyping of microscopic thermal landscapes in Brillouin light scattering spectroscopy

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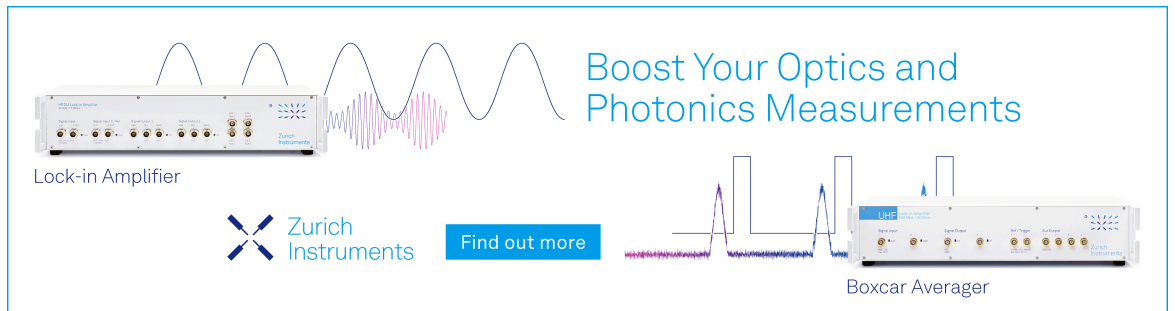
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## ABSTRACT

Since temperature and its spatial, and temporal variations affect a wide range of physical properties of material systems, they can be used to create reconfigurable spatial structures of various types in physical and biological objects. This paper presents an experimental optical setup for creating tunable two-dimensional temperature patterns on a micrometer scale. As an example of its practical application, we have produced temperature-induced magnetization landscapes in ferrimagnetic yttrium iron garnet films and investigated them using micro-focused Brillouin light scattering spectroscopy. It is shown that, due to the temperature dependence of the magnon spectrum, spatial temperature distributions can be visualized even for microscale thermal patterns.

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## I. INTRODUCTION

Temperature is crucial in many scientific fields, including biology, materials science, physics, and chemistry. By changing the temperature, it is possible to achieve both irreversible changes in the medium or to implement non-destructive reversible modifications in the system parameters, as it indirectly determines such internal quantities as saturation magnetization,<sup>1–3</sup> dielectric permittivity, resistivity, refractive index, and mechanical expansion coefficients, among others.<sup>4,5</sup> Gradients in temperature often induce transport processes, and, thus, by adjusting their spatial distribution, it is possible to tune those transport processes.

In this regard, an important task is to create specific microscopic thermal profiles in samples of different types, which can then be altered in space and time on demand.<sup>3,6–14</sup> This task occurs not only in basic research. It also arises, for instance, in the development of thermoelectric and spin-caloritronic devices<sup>15</sup> that utilize thermal energy or for prototyping functional devices that use a

heterogeneous medium to process information carried by waves passing through that medium.<sup>1,2,16–19</sup> The structure required for the latter task can be introduced into the system under study in advance using sophisticated fabrication methods.<sup>6,20–22</sup> Although the relevant methods have been continuously revised and improved over decades, they always involve considerable effort and they may irreversibly alter the samples used. A different approach for the fabrication of desired topographies is to use reversible parameters controlled by reconfigurable temperature landscapes.<sup>1,2,7,9,23</sup>

In this work, we present an experimental setup that can generate complex temperature landscapes with resolution down to the micrometer scale by projecting optical intensity patterns onto the surface of a sample. These intensity patterns are created by means of an optical wavefront modulation technique (see Sec. II A). Moreover, we have combined this technique with Brillouin light scattering (BLS) spectroscopy (see Sec. II B) to enable measuring the effect of temperature inhomogeneities on different types of wave excitations (Sec. III). BLS spectroscopy is widely used in various fields,<sup>24–29</sup>

including condensed matter physics, materials science, and biophysics,<sup>25</sup> to understand the physical properties of samples at the microscopic level.<sup>30</sup> Specifically, we applied the developed all-optical setup to manipulate and measure the characteristics of magnons, i.e., collective spin excitations, in ferrimagnetic films of yttrium iron garnet (YIG,  $\text{Y}_3\text{Fe}_5\text{O}_{12}$ ). Although this work is focused on magnons, the demonstrated approach can also be applied to phonon systems as well as to a variety of biological and material science applications if the behavior of the systems under study relies on temperature-dependent material properties.

## II. EXPERIMENTAL SETUP

Figure 1 shows a schematic view of the presented experimental setup. It can be divided into three modules: (i) the heating module, which projects an optical intensity pattern onto the sample surface to form the desired temperature landscape; (ii) the detection module for the spectroscopic observation of magnons or phonons; and (iii) the imaging module to align the sample to the probing beam of the detection module. In Sec. II, these modules will be described individually. In addition, the setup is equipped with a 2D in-plane vector magnet to allow for different magnetization regimes.

The control of these modules has been implemented by using the automation framework *thaTEC:OS* (THATec Innovation GmbH), while the following data evaluation was performed using *Python*-based software libraries such as *PyThat* and *xarray*.<sup>31–34</sup>

### A. Heating module for the creation of microscopic 2D temperature landscapes

The developed heating module creates temperature landscapes employing optical holograms and Fourier optics.<sup>1,2,7,9</sup> The holo-

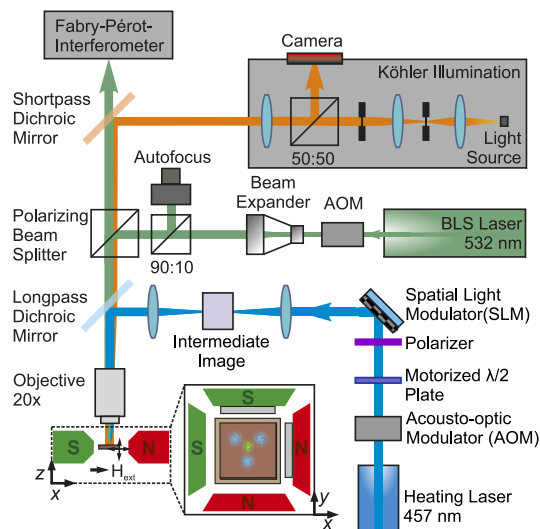
grams are formed by the utilization of phase-based wavefront modulation: A spatial light modulator (SLM), i.e., a liquid-crystal array on a silicon chip, imprints a spatial distribution of phase shifts onto an incoming planar wavefront. The corresponding phase map for a given desired intensity distribution can be calculated by means of the Gerchberg–Saxton algorithm for iterative phase retrieval.<sup>35,36</sup> By placing a lens at its focal distance away from the SLM, an intermediate image of the resulting intensity pattern is created.<sup>37</sup> By adding an iris aperture in this optical plane, the specular reflex—the part of the light that is unaffected by the phase shift of the SLM—as well as higher orders of the diffraction pattern are blocked. Due to the linear properties of Fourier optics, the aforementioned phase maps can be easily adjusted by adding Zernike polynomials, a class of orthogonal functions that describe the wavefront aberrations of rays.<sup>38–40</sup> In particular, the “tilt” terms can be used to shift the position of a given intensity landscape across the sample without the necessity for any movable mechanical parts.<sup>37–39</sup>

The combination of another lens and the microscope objective serves as a microscope configuration that projects the intermediate image onto the sample. A numerical aperture of  $\text{NA} = 0.45$  results in a spot size of about  $2\ \mu\text{m}$ .

In our experiment, we use the SLM *Hamamatsu X10468* with a resolution of  $792 \times 600$  pixels<sup>2</sup> and a pixel pitch of  $20\ \mu\text{m}$ , together with the laser *Cobolt Twist*, which emits light at  $457\ \text{nm}$ . The wavelength has been chosen since it is known to exhibit strong absorption for YIG.<sup>41</sup> It is worth noting that, in addition to thermal effects, varying the wavelength allows the study of the direct effects of optical excitation on the investigated samples. Before targeting the SLM, the beam is expanded to a diameter of  $\sim 1\ \text{cm}$ , therefore, using a large fraction of the SLM’s aperture.

This combination of small focal spot size and strong absorption results in a high density of absorbed optical power and imposes the need for additional precise control of the total heating power. While it is possible to change the laser’s output power via the driving current, this bears the risk of mode shifts, making it unsuitable for automated parameter sweeps. However, the control of optical power can be achieved by a simple sequence of a half-wave plate and a linear polarizer, where the rotation of the half-wave plate can change the polarization axis, while the linear polarizer will transmit only the polarization component required by the SLM. Due to the large beam diameter, the absorption does not damage the polarizer. By calibrating the motorized waveplate to the characteristic transmission proportional to  $\cos^2(2\alpha)$ , where  $\alpha$  is the relative angle between the transmission axis of the polarizer and the fast axis of the half-waveplate, linear power control can be achieved.

When working with thermal landscapes (especially on microscopic length scales), thermal diffusion cannot be avoided. The transport of heat along the temperature gradient, i.e., thermal diffusion, results in a blurred temperature distribution. In thermal equilibrium, the resulting size of a hotspot would depend on the thermal conductivity of the material, its heat capacity, and the distribution of heat influx. However, this effect can be somewhat softened by inducing heat in a pulsed microsecond regime. In this way, a measurement can be taken while a small volume is hot but before the heat spreads into adjacent material. After each measurement, the system thermalizes to a homogeneous temperature state, which can once again be heated quickly. We add the ability to chop the laser beam by adding an acousto-optic modulator (AOM) *G&H AOM 3080-125* to



**FIG. 1.** Schematic view of the experimental setup. The imaging beam path (orange) generates a magnified image on a CCD camera. The BLS module (green beam path) serves as the primary means of detection, while the heating module (blue beam path) is used for the creation of the temperature landscape.

the heating module, where the first diffraction order is used, which leads to negligible transmission in off-state. Since it provides rise- and fall-times below 100 ns, this is also a suitable tool to measure the dynamic effects of a rapid temperature increase or decrease.<sup>8,14</sup> However, due to the nature of thermal transport, the effective times for temperature change are highly dependent on the investigated samples and may be significantly longer.

Consequently, the presented heating module offers the means to create complex reconfigurable intensity landscapes with rise and fall times below 100 ns and the ability to continuously change the applied power in the range from 0 to 50 mW. The combination of both AOM and external power control offers the possibility of constant average power, even for altered duty cycles of the pulsed heating.

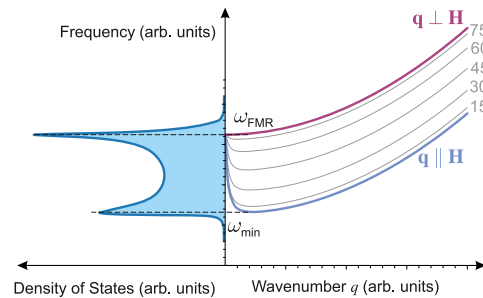
## B. Magnon detection via micro-focused Brillouin light scattering spectroscopy

In this experiment, the density of magnons is measured by means of micro-focused BLS spectroscopy with sub-micrometer spatial resolution.<sup>30</sup> This technique facilitates the frequency shift of light due to the inelastic scattering from collective excitations such as magnons. In this way, not only the overall density of particles can be detected but also the corresponding frequency, which contains further information about the character of an investigated system. While this technique can be used for phonons or magnons alike, in this work, we will focus on the detection of magnons.

The probing light source is a *Coherent Verdi* laser operating at a wavelength of 532 nm. It provides a narrow spectral linewidth and stable output power, but also has several side modes up to 7 GHz. In order to suppress these side modes, the beam passes through a polarizing beam splitter. Since scattering with magnons causes a change of the polarization,<sup>42,43</sup> the inelastically scattered component is now transmitted through the polarizing beam splitter toward the interferometer, and the side modes are blocked, thereby improving the signal-to-noise ratio considerably. The elastically scattered portion of the probing beam maintains its polarization and is used by an autofocus system to stabilize the distance between the objective and the sample.

Both the BLS beam and the SLM image (see Sec. II A) are projected onto the sample through the same microscope objective. Due to the substantial wavelength difference between the heating and probing lasers, a dichroic mirror can be used to combine both beam paths. As a result, both spot sizes produced are within a range of  $\sim 2 \mu\text{m}$ . This also implies that the system is capable of detecting waves with wavelengths as short as  $4 \mu\text{m}$ . Essentially, the high spatial resolution of the probing beam comes with the added advantage of being able to detect a wide range of wavenumbers simultaneously. Although it is impossible to resolve a single state at one given wavenumber, this approach allows us to capture a broad ensemble of spin waves (see, e.g., Fig. 2) with a single measurement. In this way, it is possible to detect magnon occupation at wavenumbers from near zero to more than  $5 \text{ rad } \mu\text{m}^{-1}$ .

In general, the probing laser, like the heating laser, can transfer heat into the system, which would distort the results. Therefore, the probing laser power has been chosen in such a way that it does not have an effect on the thermal spectrum of the YIG sample. In order to further reduce its influence, another AOM *G&H 3080-195* is inte-



**FIG. 2.** Schematic representation of the dispersion curves calculated for different propagation angles of the lowest volume spin-wave mode in a tangentially magnetized film of yttrium iron garnet with a thickness of several micrometers (right) and the corresponding density of magnon states (left).

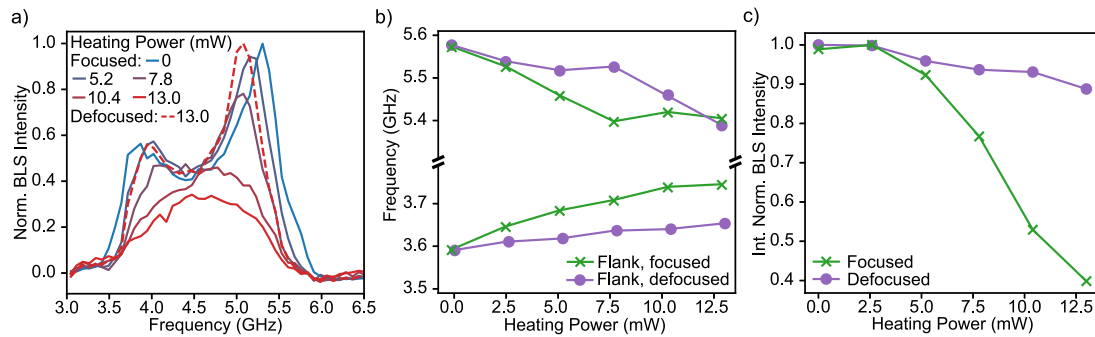
grated in the measurement beam path. In this way, it is possible to chop the measurement beam in order to concentrate the necessary optical intensity on the window of interest while avoiding unnecessary heat transfer between measurement cycles. Furthermore, in the case of YIG, the optical absorption at 532 nm is only about 10% of that at 457 nm.<sup>41</sup>

## C. Imaging system

While the scope of this article is on purely thermally induced landscapes, it should be mentioned that the majority of experiments will require the ability to align a given intensity pattern to a previously patterned structure. Accordingly, a conventional microscopy illumination module has been implemented, as shown by the orange beam path in Fig. 1. Due to the illumination with wavelengths longer than 550 nm, the illumination is mostly separated from both the probing beam path and the heating beam. However, as a result of the non-negligible reflectivity of the integrated dichroic beam-splitter, both the probing and heating beams can be imaged with high sensitivity by using a *Thorlabs CS165MU1* CCD camera. This module enables the integration of additional electrical manipulation tools such as microstrip microwave spin-wave antennas, interdigital acoustic transducers, or contacts for DC measurements.

## III. EXEMPLARY MEASUREMENTS

Section III presents various aspects of the developed setup using exemplary measurements of the thermal magnon spectrum of an in-plane magnetized YIG film with a thickness of  $2.1 \mu\text{m}$ . This spectrum is shown in Fig. 2 for the lowest magnon mode for several propagation angles. Having a quasi-uniform profile over the film thickness, this mode exhibits the largest scattering cross section compared to the higher thickness modes and, thus, makes a dominant contribution to the recorded BLS signal.<sup>28</sup> The experimental spectrum measured without heating [see Fig. 3(a)] agrees reasonably well with the density of states derived<sup>44</sup> from the theoretical spectrum<sup>45</sup> in Fig. 2. The shown density of states has two maxima: one around the frequency of ferromagnetic resonance (FMR) and one at the lowest frequency of the spectrum. These maxima correspond to the flattest parts of the dispersion curves, where magnons with different wavenumbers have close frequencies. As



**FIG. 3.** Influence of the laser-induced temperature increase. Panel (a) shows several magnon spectra measured at increasing heating powers. Both a shift of the high frequency edge of the spectrum toward lower frequencies and an overall decrease in the BLS signal can be observed. The dashed line shows a spectrum that was measured with an intentionally defocused heating laser spot. Panel (b) shows a quantitative relation between heating power and the magnitude of the corresponding frequency shift, whereas panel (c) depicts the simultaneous decrease of integrated BLS intensity in the frequency range from 3.5 to 6 GHz.

described in Sec. II B, all these magnons can be detected simultaneously due to the large wavenumber range of the micro-focused BLS module.

### A. Changing the heating power in a single spot

The straightforward approach to determine the degree to which heating affects the thermal spectrum of a YIG film is to vary the applied total laser power while both the probing spot and the heating spot are aligned. The results of a corresponding measurement are shown in Fig. 3. For the presented measurement, a repetition rate of 1 ms was chosen. In this window, the heating laser was active for 900  $\mu$ s, and the probing laser was active for the first 300  $\mu$ s. The measured intensity is the average of this measurement window.

The first important observation in Fig. 3(a) is the qualitative deformation of the BLS intensity spectrum as the heating power is increased. Most notably, both the high- and low-frequency peaks shift toward the center of the spectrum [Fig. 3(b), purple lines]. The down-shift of the high-frequency peak is in good agreement with a change in the FMR frequency  $\omega_{\text{FMR}} = \mu_0 \gamma \sqrt{H_i(H_i + M_s(T))}$ , where  $\gamma$  is the gyromagnetic ratio,  $M_s(T)$  is the temperature-dependent saturation magnetization, and  $H_i$  is an internal magnetic field, which, for an in-plane magnetized film, is equal to the externally applied field  $H_0$ . In this case, the increasing temperature reduces  $M_s$ , which in turn causes a shift toward lower frequencies.

In contrast, for the low-frequency peak at the bottom of the spectrum  $\omega_{\text{min}} \approx \mu_0 \gamma H_i$ , the observed frequency shift cannot be explained by the same effect, simply because  $\omega_{\text{min}}$  is expected to respond much more subtly to the change in the saturation magnetization.

The reason for the observed upward frequency shift may be a non-uniform magnetization of the heated sample, which leads to an increase in the magnetic field within a small heated area of the sample. The surrounding, undisturbed magnetic medium with its higher magnetization causes a demagnetizing field, which adds to the internal field  $H_i$ . As a result,  $H_i$  exceeds  $H_0$  and  $\omega_{\text{min}}$  increases.

For the highest observed heating powers, the overall shape of the spectrum begins to change. The previously clearly visible peaks at the edges of the spectrum gradually disappear. The whole spectrum

slowly morphs into a very broad peak. A possible mechanism behind this observation is that the perturbation of the structure itself is on the scale of the wavelength of the observed magnons.

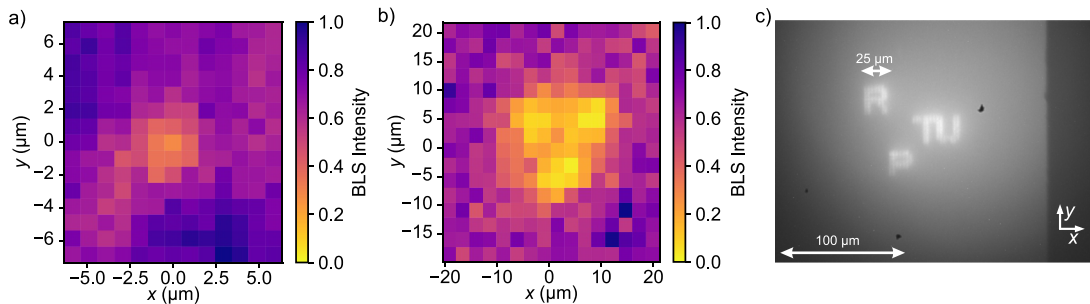
When the same experiment is repeated without the additional heating laser, a qualitatively identical behavior for the power dependence of the probing laser can be observed. Consequently, the intensity of the probing laser was chosen so that its influence on the spectrum is negligible.

Now, in this particular setup, the heating beam can easily be defocused by adding a focus/defocus ( $Z_0^2$ ) term of the Zernike polynomials to the SLM phase map (see Sec. II A).<sup>39</sup> This slight defocus smoothens the intensity gradients at the edges of the heating spot, thereby creating a more homogeneous temperature profile. Using this technique, the influence of small feature sizes can be readily suppressed. As a result, it can be seen from the red dashed curve in Fig. 3(a) and the lower purple line in Fig. 3(b) that the low-frequency peak shift is now significantly reduced, which indicates that this is indeed a feature of localized heating.

Another important observation is the overall decrease in BLS intensity [Fig. 3(c)]. However, heating can only increase the quantity of thermally excited magnons. Thus, the decrease in BLS intensity should be associated with the decrease in BLS sensitivity reported by Olsson *et al.*<sup>46,47</sup> It is notable that while Olsson *et al.* observed an intensity drop of 25% over 60 K, we see a much stronger decrease, suggesting an even stronger temperature change.

### B. Lateral scan of intensity landscapes

One of the technical advantages of reconfigurable structures is the ability to perform lateral measurements by moving the temperature landscape instead of the probing beam. For instance, in the case of constraints such as prefabricated structures, it is possible to fix the probing spot in a constant position. In this way, the change in the temperature landscape is the only factor that needs to be taken into account in the experiment. This concept holds true even for undesired features, such as impurities and surface defects, whose contribution to the BLS signals can be suppressed completely.



**FIG. 4.** Demonstration of the lateral resolution and complexity of optical intensity/thermal landscapes. (a) 2D scan of the frequency-integrated BLS intensity over a single heated spot. (b) 2D scan of three spots in a triangular configuration. The distance between the spots is  $13\ \mu\text{m}$ . (c) Intensity pattern showing the logo of the Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau. The image was obtained by projecting the reflection of the intensity landscape onto the CCD camera. The shape consists of many small spots separated by a distance of  $\sim 2\ \mu\text{m}$ .

Figure 4(a) shows the false-color representation of the frequency-integrated BLS intensity as a function of the position of the heating spot. As shown in Sec. III A, the integrated BLS intensity drops significantly when both the heating and probing lasers are aligned. The decrease in BLS intensity indicates a high temperature. Around this point, the intensity increases continuously until it reaches the ambient level. This behavior indicates that the temperature also increases continuously at greater distances from the probing point. An observed spot size of  $\sim 2\ \mu\text{m}$  agrees well with the estimated size of the probing and heating laser spots.

The same type of 2D scan is shown in Fig. 4(b), but in this case, a two-dimensional pattern of three spots arranged in the shape of an equilateral triangle with a side length of  $13\ \mu\text{m}$  is depicted. Despite the small distance between the points, a rather good contrast can be achieved, which enables a clear visual separation of the hot spots. However, between the spots, the BLS intensity does not reach the ambient level. This behavior can be attributed to thermal diffusion, which is to be expected in this type of experiment. In fact, the effect of thermal diffusion can lead to a blurred BLS intensity distribution around all three spots.

The possible complexity of the patterns that can be achieved with the presented method is illustrated by a CCD image of an intensity pattern, projected on the surface of a sample, as it is shown in Fig. 4(c). The pattern consists of a set of spots spaced at a distance of  $3\ \mu\text{m}$  in the shape of the logo of the University of Kaiserslautern, with a total size of  $100 \times 100\ \mu\text{m}^2$ . This image illustrates the power of this technique: While it is well suited for creating small features, it can also be used to create structures with form factors nearly two orders of magnitude larger.

#### IV. CONCLUSION

We present an all-optical experimental setup for direct BLS observations of quasiparticles such as magnons in reconfigurable microscopic thermal landscapes. This setup provides the capability to quickly create arbitrary landscapes for scientific measurements, as well as rapid prototyping, which can significantly reduce the time and opportunity costs in the development and measurement cycles.

As a proof of concept, the study of thermal magnons under localized heating reveals a qualitative change in their spectrum when

the temperature is strongly increased in the microscopic region. This effect is not observed when the same amount of heat is distributed over a slightly larger area. Furthermore, we have shown the spatial characterization of temperature landscapes that reveals a strong thermal contrast at the micrometer scale. Although we have focused on relatively simple model structures in this work, much more complex temperature profiles can be created using this heating technique.

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#### AUTHOR DECLARATIONS

##### Conflict of Interest

The authors have no conflicts to disclose.

#### Author Contributions

**Matthias R. Schweizer:** Conceptualization (lead); Data curation (equal); Formal analysis (supporting); Investigation (equal); Methodology (lead); Software (lead); Validation (supporting); Visualization (supporting); Writing – original draft (lead); Writing – review & editing (equal). **Franziska Kühn:** Data curation (equal); Formal analysis (lead); Investigation (equal); Methodology (supporting); Software (supporting); Validation (supporting); Visualization (lead); Writing – review & editing (equal). **Malte Koster:** Conceptualization (supporting); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (equal). **Georg von Freymann:** Conceptualization (supporting); Funding acquisition (equal); Methodology (supporting); Project administration (equal); Resources (equal); Supervision (supporting); Validation (supporting); Writing – review & editing (equal). **Burkard Hillebrands:** Conceptualization (supporting); Funding acquisition (equal); Methodology (supporting); Project administration (equal); Resources (equal); Supervision

(supporting); Validation (supporting); Writing – review & editing (equal). **Alexander A. Serga**: Conceptualization (supporting); Funding acquisition (equal); Methodology (supporting); Project administration (equal); Resources (equal); Supervision (lead); Validation (lead); Writing – original draft (supporting); Writing – review & editing (equal).

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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