as holography, sensing or imaging, a point source of coherent light that emits light in all directions is a better choice or even necessary. The Bragg-onion laser with omnidirectional dielectric cladding is a natural candidate for such a source. We have therefore measured the angular dependence of the laser emission intensity and wavelength. This was done by introducing a glycerol dispersion of CLC microlaser droplets into a cylindrical glass tube. The angular dependence of the emitted light from a single droplet was measured by rotating the CCD camera, or an optical fiber guiding the collected light into the spectrometer, around the tube. The results shown in Fig. 5(a) clearly indicate that the intensity is highly uniform across the entire solid angle. The wavelength of the emitted light is also independent of the direction of the emission. We have not measured in detail the emitted intensity along the direction of the defect itself.

Furthermore, liquid crystals have large response to external stimuli, such as electric field and temperature. In an earlier work, we have shown that electrically tunable whispering-gallery-mode microcavities can be made from nematic liquid crystal droplets in a polymer [31]. The cholesteric onion laser is also highly tunable, as the cholesteric pitch usually depends on the temperature [32] and can also be set by the chiral dopant concentration. In a mixture of nematic LC and a chiral dopant at the right concentration, together with the proper dye, lasing from UV to IR has been achieved in planar cells of CLCs [33, 34], and it should also be possible to achieve this in CLC onion microdroplets. By changing the temperature we can, in our case, tune the emission by $\sim$35 nm (Fig. 5(b)). The spectral shift is almost linear with temperature (3.5 nm/K) and completely reversible. Phototunability has also been demonstrated in cholesteric lasers [35] and should be interesting for application in phototunable spherical lasers.

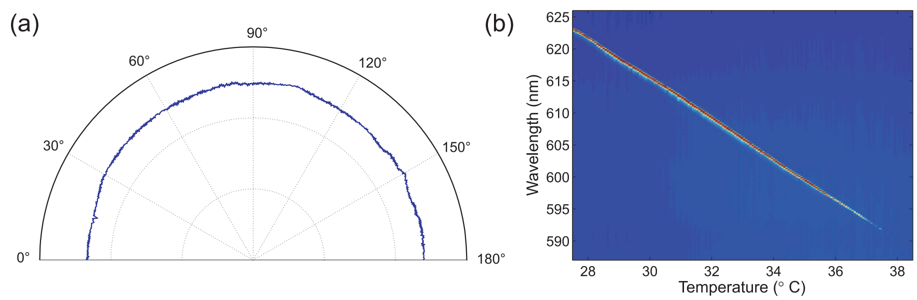


Fig. 5. (a) Lasing intensity from a single 50 $\mu$m CLC droplet as a function of the angle of rotation of the photodetector around the axis of the cylindrical tube, containing the microdroplets. (b) Lasing spectra as a function of temperature. At higher temperatures the laser line is shifted outside the optimum wavelength region of the dye used, so the laser emission ceases.

## 4. Conclusion

In conclusion, we have demonstrated 3D lasing from dye-doped cholesteric microdroplets with a Bragg-onion configuration of the refractive index. The lasing wavelength is determined solely by the cholesteric pitch. The laser light is emitted from the center of the CLC microdroplet in all directions, thus the laser is acting as a coherent, point-like, and omnidirectional source of light. Because of the temperature dependence of the helical pitch of the cholesteric, the microlaser wavelength is tunable by changing the temperature, the tuning range being several tens of nanometers. A number of applications of the cholesteric onion microlasers is anticipated, such as holography, telecommunications, optical computing, imaging, sensing and even as a material for paints or light sources that emit coherent light in all directions. By coating the droplet with a protective shell or by polymerizing the liquid crystal itself, a more mechanically stable mi-

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crolaser could be made, useful for example in biological imaging. Further studies could include a fluorescent/plasmon particle as an active core, nonlinear core material for second-harmonic generation, suppression of spontaneous emission and coupled regular arrays of thousands and even millions of CLC microlasers. We anticipate that by using better materials and optimized material parameters, such as the concentration of the chiral dopant and of the fluorescent dye, it will be possible to further reduce the size and increase the tunability and the functionality of the cholesteric onion lasers. The CLC onion microlasers could also be combined with optical fibre waveguides to collect radiating light into the waveguides. The proposed procedure of making a CLC onion microlaser by mechanical mixing is simple and straightforward and produces millions of microlasers in a fraction of a second.

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