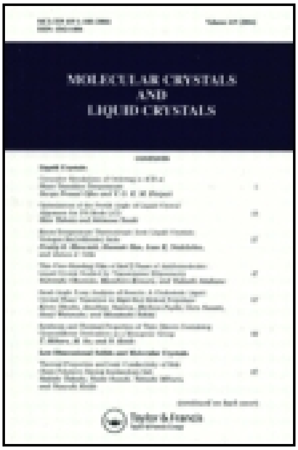

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George V. Lukianoff [a]

[a] IBM Components Division East Fishkill Facility Hopewell Junction, N.Y., 12533

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Information Content and Resolution Aspects in Thermal Mappings using Cholesteric Compounds‡

GEORGE V. LUKIANOFF

IBM Components Division
East Fishkill Facility
Hopewell Junction, N.Y. 12533

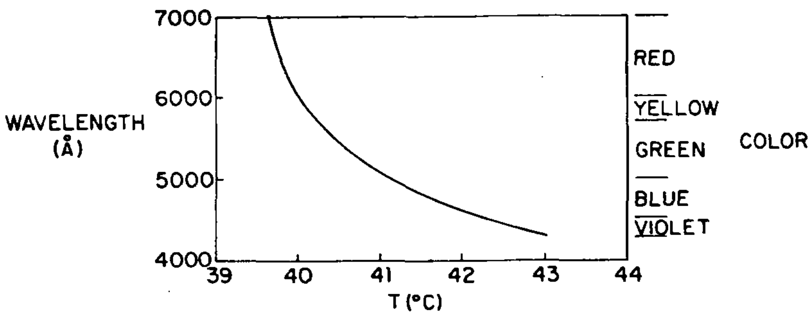
Abstract—Information content in a thermal mapping using cholesteric compounds is a function of the spatial and amplitude resolutions of temperature-dependent light scattering of cholesteric thin coatings. The reported experimental work was guided to derive above resolution limits in order to obtain maximum information content. The experiments yielded a one micron spatial resolution and nine amplitude levels. (The latter number can be significantly increased by application of special techniques.) It is shown that high sensitivity compounds can resolve 0·007 °C which can be displayed in a form of isocontour maps. A need for high-resolution mapping is illustrated by an example from electronic industry. Factors adversely affecting mappings are described. Information content, in a thermal mapping, is derived from the above data yielding a density of 10^9 bits per square centimeter.

Introduction

The selective color scattering as a function of temperature of cholesteric compounds has attracted the attention of many branches of science and industry. The compounds applied in form of thin coatings on to objects of investigation display colorful thermal maps. The span of colors of the visible spectrum in these maps represents a specific temperature-spread characteristic for each individual compound. Each color uniquely represents a temperature and this relationship can be shown by a λ-vs-T

‡ Presented at the Second International Liquid Crystal Conference at Kent State University, Kent, Ohio, August 16, 1968.

curve. A typical curve is shown in Fig. 1. This relatively new technique has quickly passed through its curiosity phase to become an important and useable tool.



COLOR CALIBRATION FOR VISUAL WORK

COLORLESS-RED	39.5	GREEN-CENTER	40.6
RED-CENTER	39.7	GREEN-BLUE	41.2
RED-YELLOW	40.0	BLUE-CENTER	42.0
YELLOW-CENTER	40.1	BLUE-COLORLESS	43.0
YELLOW-GREEN	40.2		

1. Calibration curve and table.

Depending on the field of usage, different requirements were imposed upon the compounds. However, the common goal was the same to collect thermal information of the mapped objects.

The classic Information Capacity Equation is given by $I = ld\,A^{\nu}$ which is a logarithm to the base 2 of the number of distinguishable color levels, raised to the power of the spatial resolution capability of the cholesteric compounds.

To determine the Information Capacity, the experiments were correspondingly arranged into two groups:

1. Spatial resolution measurements.
2. Color-amplitude levels measurements.

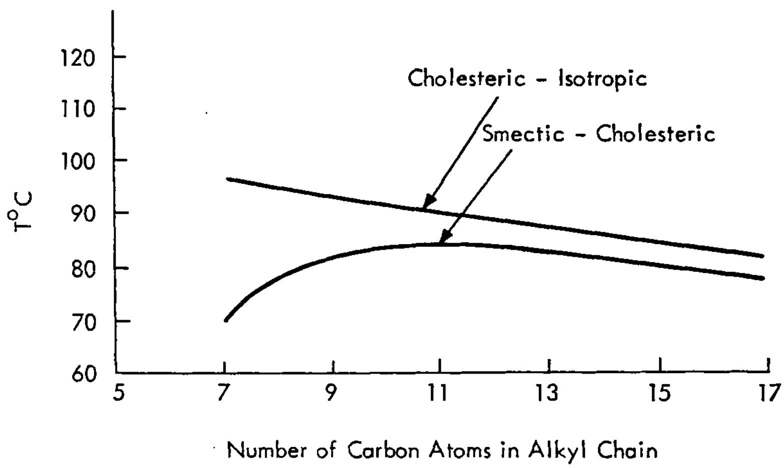
Spatial Resolution

Spatial color-temperature resolution has three categories:

1. Temperature band, within which the entire color spectrum is displayed.
2. Space occupied by the color band.
3. Color separation within the band.

The temperature band within which the color spectrum is displayed is a function of the composition of the cholesteric molecules. It depends on the amount of carbon atoms in the molecular chains and upon the purity of the material. A typical dependence is shown in Fig. 2. It has been reported in technical literature that compounds have been synthetized with temperature bands as narrow as 0.1 °C and as wide as 50 °C. The 0.1 °C compounds, having higher temperature resolution, contribute more to the information collection.

The space required by the compounds to display full-color spectrum depends on the thermal gradients of the mapped object and on the structural characteristics of the compounds. The minimum size of this space determines spatial resolution capabilities of the compounds. To measure it, a test pattern was designed and made by etching chromium resistors on glass and silicon substrates. The resistors were arranged in a set of slowly varying line widths and spaces, constituting a pattern of variable spatial



2. Color-temperature band as a function of carbon atoms.

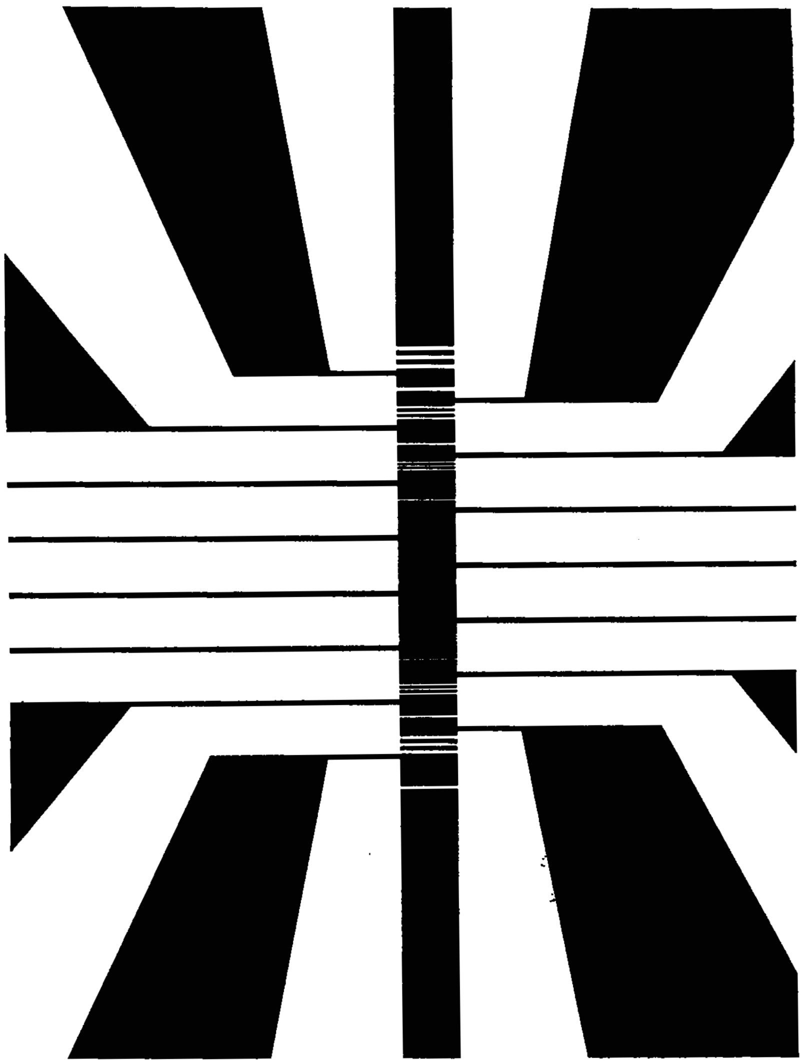
frequencies and spatial pulses. The range of frequencies was from 0.5 to 100 cycles per millimeter—corresponding to wavelengths between 2 and 10×10^{-3} mm. In addition to the above set, there was an isolated line of one micron in width (Fig. 3).

The last category of the spatial resolution is the separation of individual colors within a band. The same test patterns (described above) were utilized. The temperature differences between the chromium lines and spaces were controlled by power input and cooling arrangement, and a degree of differences was maintained necessary to ensure full-color separation. Colors were separated down to the highest frequency of 100 cycle per mm (Fig. 4). Upon powering the isolated one-micron line, a thermal gradient was established on the silicon so that the red-color width was equal to one micron.

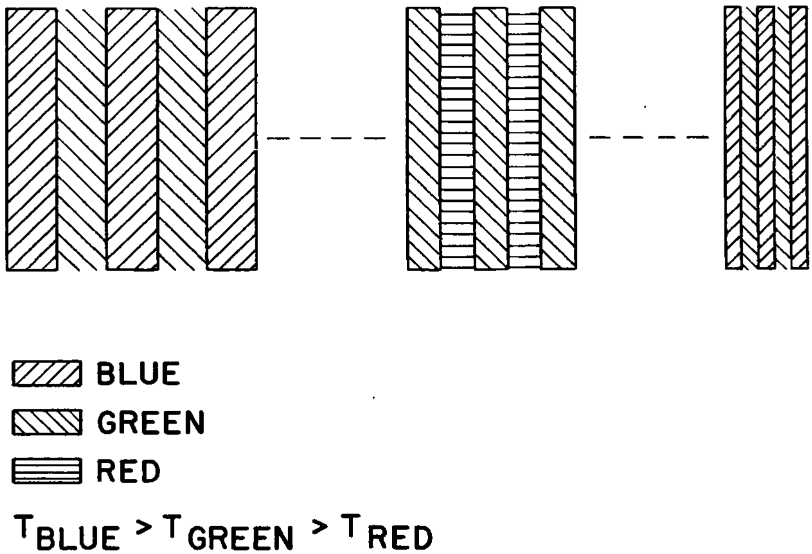
The one-micron size approaches wavelength dimensions which would be, for the optical part of the experiment, a fundamental limit. A question arises: What is the fundamental limit of the cholesteric structure's ability to sustain structural gradients related to the differences between adjacent helical lengths?

In general applications, color distributions correspond to temperature differences of the mapped objects, and, temperature determination corresponds to well identified color regions, viz. color transistions and centers of well defined colors A corresponding set of points is shown in the table of Fig. 1. There are nine possible readings; however, in practice, only seven are usually present.

Another way of separating individual colors is by use of monochromatic illuminations. For this experiment, a temperature difference was applied to a plain object to create a thermal gradient to obtain a well defined color band (in white-light illumination). Upon establishing the color distribution, the sample was illuminated with a number of narrow-band monochromatic beams of approximately 12 Å at the half-amplitude point. The reflected lines were observed to be much wider than the space corresponding to 12 Å—about 15 times wider and space wise corresponding to about 200 Å of the color band. This value sets the color resolution limit.

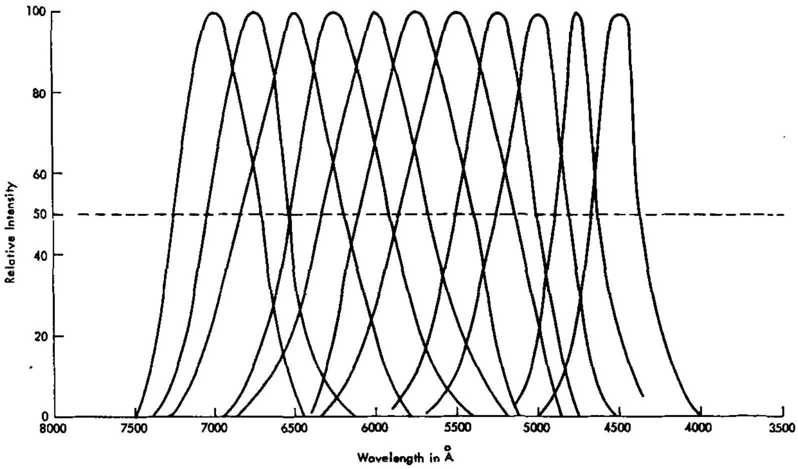


3. Spatial resolution test pattern.



4. The resolved colors-temperatures.

To demonstrate it consider a sequential illumination by a set of monochromatic lines separated by 250 Å and covering the entire visible spectrum. Each reflected line is scanned to obtain an intensity-distribution profile plotted on a common graph (Fig. 5). The large overlap of the curves, especially in the red region, shows that if they were simultaneously used, they would not be resolved (except in the blue region). Consequently, a larger beam separation and/or slimmer intensity distribution are needed. To achieve the latter, a well collimated incident beam and relatively thin coatings should be used. The normal distribution curve results probably from the randomly oriented helixes within the bulk of the coatings. If it were possible to orient the helixes by an external factor, the intensity-distribution curves would shrink. Some experimentation was made with the nonlinear effects of the photographic films so that only the central part of the curves was reproduced. This approach permitted narrowing the line width by about 40%, or, in effect, narrowing from 200 to 120 Å. As a



5. Cholesteric coating's response to narrow band (12–15 Å) illumination.

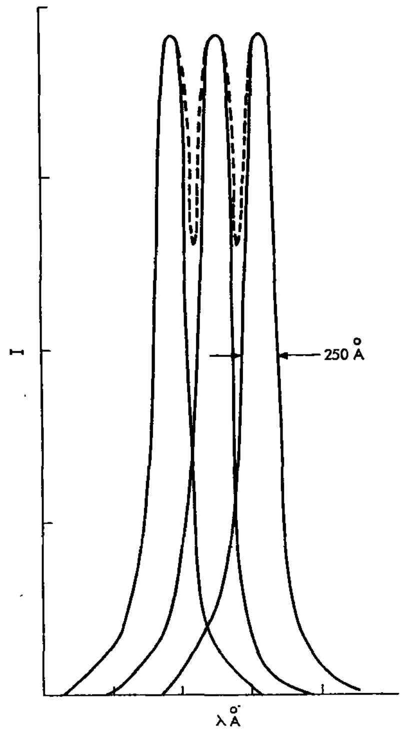
result, the number of resonable color lines per visible spectrum could be increased to 12–15.

In practice, each monochromatic band represents an isothermal contour line. The use of medium sensitivity compounds of, say 3 °C of total response, above resolution implies a spatial differentiation of up to 0·2 °C; and for high-sensitivity compounds of 0·1 °C total range, resolution up to 0·007 °C is implied. This number can be significantly increased by use of graphic or electronic extrapolation techniques utilizing well defined centres of the curves.

Temperature-Amplitude Resolution

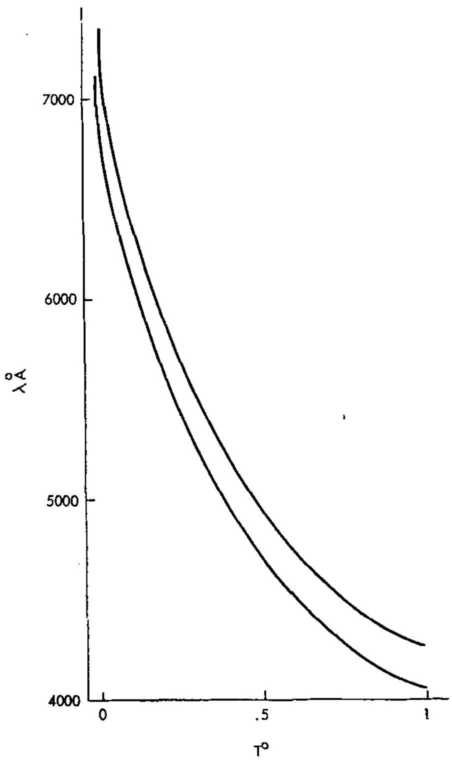
The second resolution term in the Information Equation is that of the number of distinguishable amplitude levels. The scattered color associated with a specific temperature is distributed in a bell-shaped curve with a half-amplitude point of about 200–250 Å See Fig. 6*a*. This band width is the limiting factor in amplitude resolution, permitting nine amplitude levels to be resolved. This frequency spread introduces an uncertainty into the color-temperature relation. Graphically, it can be represented by a broadening of the calibration curve (wavelength vs temperature) See Fig. 6*b*.

To increase the resolution, a smaller-frequency spread is required. Assuming that the spread comes partly from the differences in orientation of the helixes in the ordered localized regions, a means should be devised to align the helixes in a preferential direction. Using individual curves with relatively



6*a*. Color scattering curves.

well defined peaks, frequency determination can be made with an accuracy of ± 25 Å, i.e. ± $\frac{1}{20}$th of the total color spectrum—making it possible to distinguish about 60 color-amplitude levels. However, it should be understood that this high number (for the time being), is applicable to single readings, and cannot be used in a continuous-type mapping.



6*b*. Effect of color scattering on calibration curve.

Temporal Response

For the sake of completeness of the information data, Temporal Response should be mentioned. The ability of the cholesteric compounds to follow changes of the thermal patterns is reported (by J. L. Fergason) to be about 30 milliseconds of 33 cycles per second. This speed is not excessively high; however, it is faster than the visual response—thus making it suitable for visual speed observations.

Adverse Factors

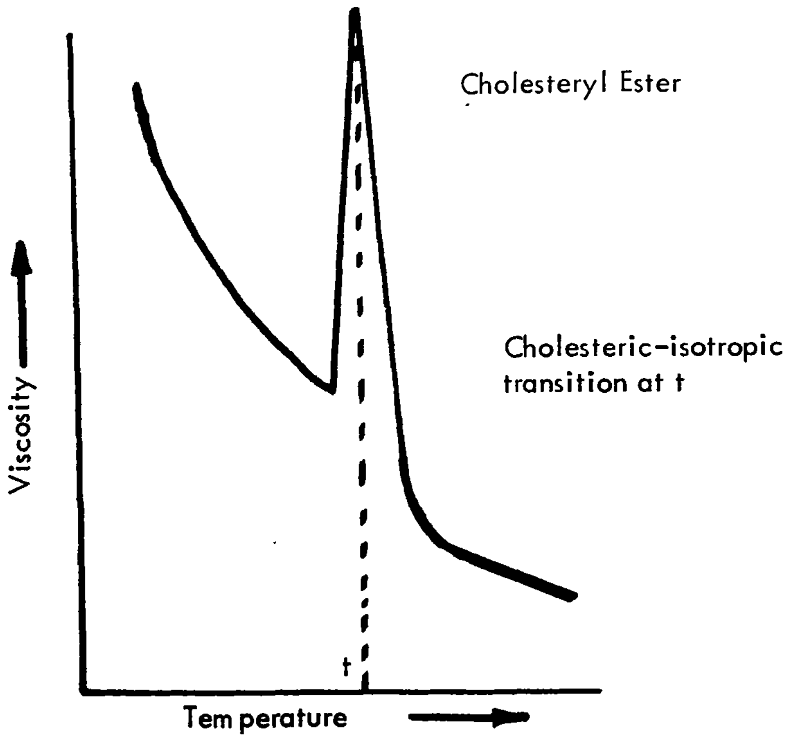
Several factors adversely affect spatial and amplitude resolutions. Some of them are related to the basic characteristics of the compounds. The most pronounced one is the response to a continuous-temperature distribution of a substrate by a display of isolated, rather than continuous, specs of color. The size of the specs and their separation determine the highest detectable spatial temperature frequency. The specs by themselves are not the limiting factor; one can obtain color differences within a spec. However, between the specs, there is no color, i.e., no information. The application problem is: How to get the specs to be closely spaced and located in the proper areas; and the associated research problem is: How to synthesize compounds with continuous-color representation?

As far as specs are concerned, it can be expected that they have high resolution within them, since the color effects are of a molecular alignment nature (in the order of illumination wavelengths). A materials question arises: How sharp a molecular structure transition can take place? Or: What is the highest structural gradient which a compound stressed can take?

Another factor is the one associated with surface tension. The viscosity-vs-temperature curve has a sharp increase at the cholesteric-isotropic transition (Fig. 7). This increase in the course of several heating cycles (during which a substance passes through the local peak tension) causes cholesteric coating to form blobs which obscure color differentiation and decrease spatial resolution.

As an example of the experimental technique difficulties which every user has to cope with, consider two factors: coating thickness and coating non-uniformities.

The thickness of a deposited coating has a pronounced effect on the spatial and amplitude resolutions. The criterion for the proper coating thickness is its color-temperature representation. When the coating's color truthfully represents a sample's temperature amplitude, and spatial resolution, the coating is good. The proper thickness of a coating is a relative quantity, and is



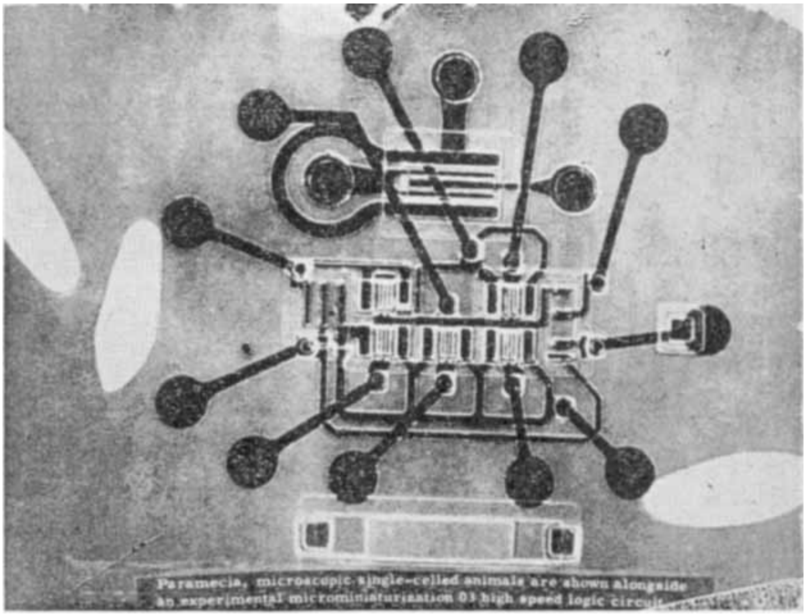
7. Temperature dependent viscosity curve.

judged by its relation to the sample geometry and thermal energy availability.

Coating's non-uniformities manifest themselves in faulty color patterns, which are apt to create a false representation of temperature distributions.

Mapping Applications

A need for the high-information capability of the mapping compounds can be easily explained by stating the specific requirements, dimensions, and element densities of the mapped objects. Consider as an example mapping in electronics and, for an object,



8. A monolithic micro-circuit (localized object densities of 5000 objects per linear centimeter).

a monolithic mocrocircuit (Fig. 8). The largest dimension of the largest transistor is 30 microns, whereas the smallest dimensions of the smallest elements is less than two microns. The latter implies localized object densities of the order of 5000 objects per linear centimeter. This number sets the spatial resolution requirements to mapping compounds. As stated above, the obtained one-micron resolution meets this requirement. It is felt that by use of the liquid-crystal method, which is capable of resolving temperature difference in the order of thousandths of a degree, can adequately handle such small temperature differences.

Plugging the experimental data into the Information Equation (presented in the introduction) gives an information density of

$$I = \mathrm{l}d\, A^{\nu} = \mathrm{l}d\, 10^{4} = 3.32 \times 10^{4}$$

$$= 3.32 \times 10^{4} \text{ bits per linear centimeter}$$

$$= 10^{9} \text{ bits per square centimeter}$$

The cholesteric compounds offer a high-information density measurement method which has the possibility in the future to become the highest thermal information collecting technique.

Acknowledgments

I would like to express my thanks to R. Lange for performing part of the experiments for this investigation, and V. Dhaka for permission to use his circuit photograph shown in Fig. 8.