Fiber optic development for use on the fiber optic helmet-mounted display

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Abstract. The fiber optic helmet-mounted display (FOHMD), developed by CAE Electronics Ltd. for the U.S. Air Force Human Resources Laboratory, requires large-format coherent fiber optic cables to support the demanding full color, high-resolution display requirements plus provide flexibility, durability, and light weight and be up to 2.1 m in length. Currently, FOHMD cables are linear arrays of multifibers separated by inactive material spacers to achieve a lightweight cable with a large cross section. This multifiber approach, with 5 μm diameter individual fibers, delivers high performance by using chromatic multiplexing to improve resolution and wash out the inactive spacer structure. Reduced fiber breakage and improved fiber alignment have also significantly increased the optical performance of the system. To achieve still higher image quality, a technically more difficult process is also being explored. Several small experimental cables have been assembled using leachable, fused multifibers arrayed in a hexagonal pattern. Improved cable drawing technology will allow for precise assembly of hexagonal components into a full format bundle. This new fiber optic cable technology has the potential of providing image transmission capability equal to 10 million pixels. When coupled with chromatic enhancement, the FOHMD optics will deliver a resolution equal to 1.5 arcmin per pixel over a large field of view.

Subject terms: electro-optical displays; helmet-mounted displays; fiber optics; chromatic multiplexing; dynamic enhancement; resolving power; fixed-pattern noise; wound/leachable fiber bundles.

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CONTENTS

1. INTRODUCTION

The bubble canopy on modern tactical aircraft and the larger visual field available in the new lightweight helmets allow combat pilots unprecedented instantaneous and total fields of view (FOV). The detail and acuity necessary to supply a pilot with a simulation of this environment is quite demanding and, in fact, cost prohibitive if conventional techniques are applied. Projecting the hundreds of millions of pixels of information bombarding a pilot from outside the typical bubble canopy is neither technically nor economically feasible and, fortunately, not necessary. An excellent technique for reducing simulation costs is to match the information content of the scene presented with the pilot's point of gaze.[1,2] The rapid reduction on off-axis visual acuity in the human visual system means that only a few channels of imagery are needed to supply each eye with an adequate scene if they are properly formatted and servoed to the point of gaze, thus providing an area-of-interest (AOI) based simulation.[3]

2. SIMULATOR SYSTEM DESCRIPTION

The fiber optic helmet-mounted display (FOHMD) was designed to support Tactical Air Force requirements.[4] Light valve projectors are mounted behind the pilot to provide the imagery for two fiber optic cables attached to helmet optics. An optical helmet tracker is used to determine the pilot's head position and, hence, the background scene for the computer image generator to generate. The AOI imagery is then inset into the background and servoed to match the point of gaze as determined by an eye-tracker mounted on the helmet. Figure 1 shows how the fiber optics are used as flexible conduits for the combined imagery.[5]

This approach yields a full color, high-brightness, high-resolution composite scene with a large instantaneous FOV. To completely transmit the composite scenes imaged by the off-helmet light valve projectors, the fiber cables require a 24 mm by 19 mm format, containing over four million fibers.

The Phase IV generation of FOHMD, first delivered to the Air Force Human Resources Lab (AFHRL) at Williams Air Force Base, Ariz., in 1986, is capable of presenting an 82.5°

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14. ABSTRACT
The fiber optic helmet-mounted display (FOHMD), developed by CAE Electronics Ltd. for the U.S. Air Force Human Resources Laboratory, requires large-format coherent fiber optic cables to support the demanding full-color, high-resolution display requirements plus provide flexibility, durability, lightweight, and be up to 2.1 m in length. Currently, FOHMD cables are linear arrays of multifibers separated by inactive material spacers to achieve a lightweight cable with a large cross section. This multifiber approach, with 5 m diameter individual fibers, delivers high performance by using chromatic multiplexing to improve resolution and wash out the inactive spacer structure. Reduced fiber breakage and improved fiber alignment have also significantly increased the optical performance of the system. To achieve still higher image quality, a technically more difficult process is also being explored. Several small experimental cables have been assembled using leachable, fused multifibers arrayed in a hexagonal pattern. Improved cable drawing technology will allow for precise assembly of hexagonal components into a full format bundle. This new fiber optic cable technology has the potential of providing image transmission capability equal to 10 million pixels. When coupled with chromatic enhancement, the FOHMD optics will deliver a resolution equal to 1.5 arcmin per pixel over a large field of view.

15. SUBJECT TERMS
Fiber Optic Helmet Mounted Display; FOHMD; Fiber optics; Electro-optical displays; Helmet-mounted displays; Chromatic multiplexing; Dynamic enhancement; Resolving power; Fixed-pattern noise; Wound/leachable fiber bundles.

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Fig. 1. Detail of the helmet and fiber optics.

horizontal by 67° vertical instantaneous FOV to each of the pilot's eyes. Since the 25° horizontal by 19° vertical eye-slaved AOI is capable of addressing most of this area, the resolution of the entire fiber optic cable must equal the resolution required to support the AOI.

The Phase V generation of the FOHMD, delivered to the AFHRL in Dec. 1988, provides each of the pilot's eyes with an enlarged background channel instantaneous FOV of 100° horizontal by 80° vertical while keeping the AOI the same size as the Phase IV system's. With a 38° stereoscopic overlap, this increases the Phase V system's instantaneous FOV to 160° horizontally by 80° vertically as compared with Phase IV system's 40° overlap and 126° horizontal by 67° vertical FOV. This enlargement places even greater resolution and optical quality requirements on the fiber optic cables.

3. FIBER OPTIC BUNDLE SPECIFICATIONS

Supporting an eye-slaved AOI-based system with high brightness and full color dictates a number of characteristics besides a large format. The fiber optic cables were required to transmit white light at 10% efficiency with a blue light (440 to 495 nm) transmission efficiency 70% that of the white light. The numeric aperture was required to be equal to or greater than 0.66. In the quality viewing area (within a 30° radius of nasal center) greater than 0.1% broken or missing fibers and any double or missing skips would be unacceptable. A fine diffusion grind was to be applied to the helmet end of each cable and end flatness needed to be better than 12 μm. Finally, incoherency discontinuities needed to be less than 25 μm and more than three incoherent rows of 20 μm or greater would be unacceptable in the quality viewing area.

Another important measure of cable performance is resolving power. Paul Weissman, optical designer for Marty Shenker Optical Design (an FOHMD program subcontractor), has concluded that, based on the overall visual requirements of the helmet-mounted display, the image cable using chromatic enhancement must have 50% modulation at 100 line pairs/mm. (ℓp/mm) Using the optical bench test assembly set up at Schott Fiber Optics (SFO), resolving power of the cable is determined by measuring the cutoff frequency when imaging a United States Air Force (USAF) standard resolution test pattern. A typical image is shown in Fig. 2. This USAF standard resolution test pattern method, which can be theoretically correlated with modulation transfer, is felt to be most informative because it is a function of fiber core size, fiber misalignment (incoherency), chromatic multiplexing, and background noise. Cutoff frequency is a key criterion used in evaluating cable performance in development work at SFO.

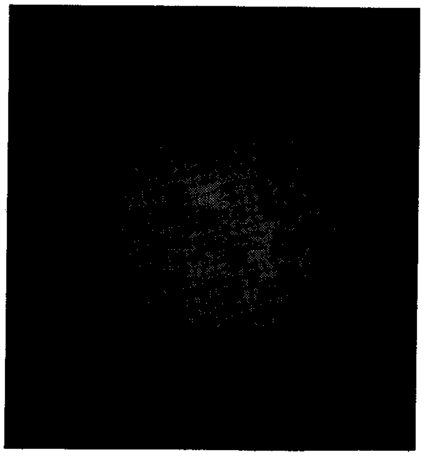
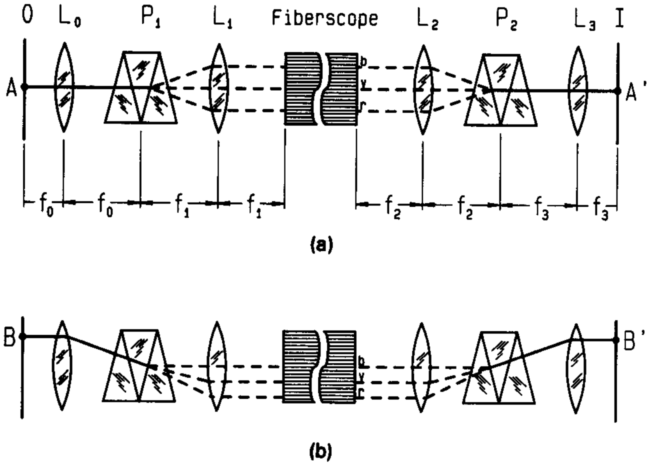


Fig. 2. Fiber optic cable image of USAF standard resolution test pattern.



(a)

(b)

Fig. 3. Schematic diagram of chromatic multiplexing system. Blue, yellow, and red rays are indicated by b, y, and r, respectively.

4. OPTICAL THEORY

In both FOHMD systems, chromatic multiplexing is used to smooth out the skip-layer structure and increase resolution. With chromatic enhancement, zero deviating dispersing prisms are placed before and after the fiber optics to distribute spectrally individual pixels over multiple fibers and recombine them after they exit the fiber optic cable. A schematic diagram of a fiber

TABLE I. Theoretical modulation at 100 ℓp/mm for various fiber sizes and misalignments.

Fiber Core	Standard Deviation of Misalignment (Microns)					
Core Diameter	0	1	2	3	4	5
3	.80	.65	.36	.13	.03	.01
5	.52	.43	.24	.08	.02	.00
7	.26	.21	.12	.04	.01	.00
9	.08	.07	.04	.01	.00	.00
11	.01	.01	.00	.00	.00	.00

TABLE II. Theoretical cutoff frequency in line pairs per millimeter for various fiber sizes and misalignments.

Fiber Core	Standard Deviation of Misalignment (Microns)					
Core Diameter	0	1	2	3	4	5
3	310	240	165	115	90	75
5	185	170	135	105	85	70
7	130	125	110	95	80	65
9	105	100	95	80	70	60
11	85	80	75	70	65	60

optic system using chromatic multiplexing as discussed by Koester[6] is shown in Fig. 3. In Fig. 3, L_0, L_1, L_2, and L_3 are lenses; P_1 and P_2 are matching "direct vision" prisms.

Based on the experimental results of this initial work, the empirically derived equations for determining resolving power (R. P.) of chromatic enhanced fiber optics are

$$\text{R. P. } (\ell\text{p/mm}) \approx \frac{1000}{d} \; ,$$

$$\text{R. P. } (\ell\text{p/mm}) \approx \frac{1250}{D} \; ,$$

where d is the fiber core diameter and D is the fiber diameter, both measured in micrometers.

The optical transfer properties of perfectly aligned fiber optic cables have been derived by Drougard, who developed a theoretical basis for a dynamic MTF in which both the entry and exit faces of a fiber cable are moving in a synchronous, random pattern.[7] A statistical approach used to characterize image transmission through misaligned fiber was later developed by Marhic, Schacham, and Epstein.[8] They have proposed that the average MTF for a fiber optic cable with Gaussian misalignment is

$$H_c(f) = \frac{[2J_1(\Pi fd)]^2}{[\Pi fd]^2}\exp(-2\Pi^2 f^2 r^2) \; ,$$

where $H_c(f)$ is the average dynamic MTF, $J_1(\cdot)$ is the first-order Bessel function, d is the fiber core diameter, f is the spatial frequency, and r is the standard deviation of fiber misalignment.

Even though this model was developed for dynamic enhancement, it is here being applied to chromatic enhancement with the following qualification: Dynamic enhancement results in a spatially invariant line spread function. The line spread function for chromatically enhanced images is spatially invariant only for test pattern lines that lie perpendicular to the direction of dispersion. Because of its directionality, the chromatic enhancement does not fully "wash out" extended image patterns that lie parallel to the direction of dispersion. Therefore, the resolving power of chromatically enhanced fiber optic cables is found to be slightly lower for test pattern lines that are parallel to the direction of dispersion.

For a better understanding of the MTF equation, we calculate the modulation for fiber optic cable designs to see how core size and misalignment affect performance. Table I presents the modulation at 100 ℓp/mm for various core sizes and misalignments. As can be seen, the model predicts very rapid falloff in optical performance for increases in fiber size and/or misalignment.

The available equipment can now measure the cutoff frequency for fiber cables in a chromatically enhanced imaging system. The cutoff frequency is the highest spatial frequency transmitted through the cable that can be visually resolved. Table II presents the theoretical cutoff frequency for various fiber core

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TABLE III. Summary of kerf loss measurements, spacer material, and resolution test results for various cables.

Cable No	Spacer Material	Kerf Loss	Test Pattern Cutoff Freq. (line pairs/mm) Vert Pattern	Test Pattern Cutoff Freq. (line pairs/mm) Horz Pattern
1371-1	Glass Fiber	0.045	80	50-60
2334-1	Glass Fiber	0.017	110	71
2334-2	Glass Fiber	0.019	110	71
1371-4	25 micron resilient	0.017	110	90
1371-5	20 micron resilient	0.018	110	90

Note: The cutoff frequency for cable 1371-1 was taken from measurements made at AFHRL. The other cutoff frequencies were measured at SFO. Cables had a fine grind on the helmet-mounted end for diffusion purposes.

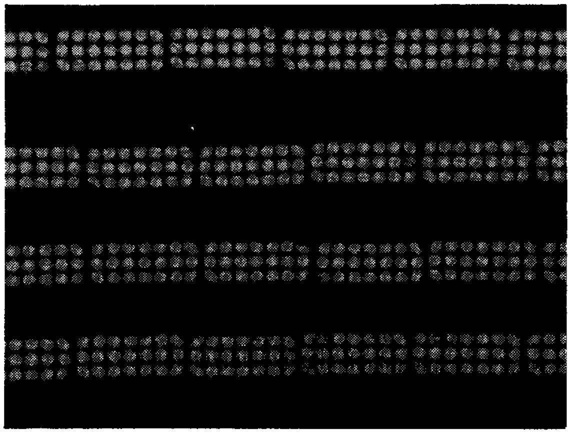

Fig. 6. A 3×7 rectangular multifiber 20 μm high.

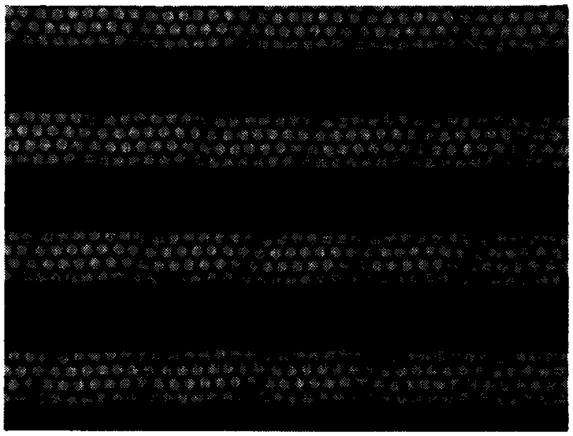

Fig. 7. A 4×7 element rhomboid multifiber (magnification is 400×).

properties: (1) provide uniform spacing between rows of multifibers (approximately 25 μm); (2) maintain multifiber alignment during the format bonding (potting) cycle; (3) maintain stability during final assembly, polishing, and subsequent use; and (4) minimize fiber breakage in the bonded region.

Finding a suitable material proved challenging. Several materials evaluated had at best three out of four key properties. Recently, however, a proprietary machined Mylar spacer material was developed that has all four properties. This spacer was used in combination with rhomboid-shaped multifibers to build a half-size prototype cable with a resolving power that reached the levels predicted by the theoretical and empirical models.

Figure 8 shows a section of the cable format, illustrating how the multifibers are arranged in a highly ordered fashion. Figure 9 illustrates the improvements made in the resolving power of prototype cables delivered over the identified time period.

The data for Fig. 9 (listed in Table IV) were taken on MTF equipment at SFO. Both the entry and exit faces of the cables were polished. For this data, vertical test patterns lie perpendicular to the direction of dispersion (multiplexing) and horizontal test patterns lie parallel to the direction of dispersion.

It can be seen that a major improvement in optical performance resulted when the rhomboid-shaped multifiber was introduced. The second improvement came with the introduction of the machined Mylar spacer material.

7. LEACHABLE BUNDLES—THE FUTURE

Despite the progress made with skip-layer-wound cables, it was felt that the limit for this technology was being reached, principally because of the remaining fixed-pattern noise. It was decided that an entirely different technology, the leachable approach, would be needed to achieve further improvements. Small

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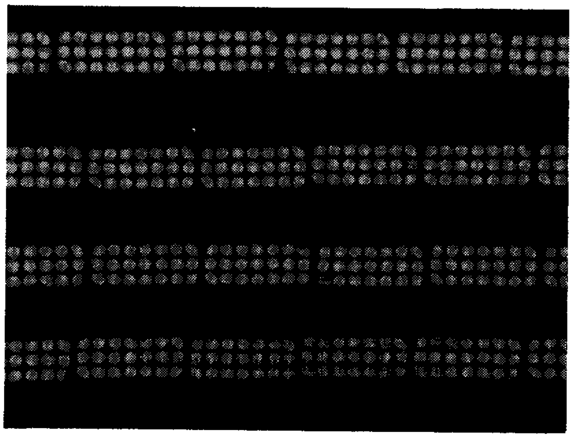

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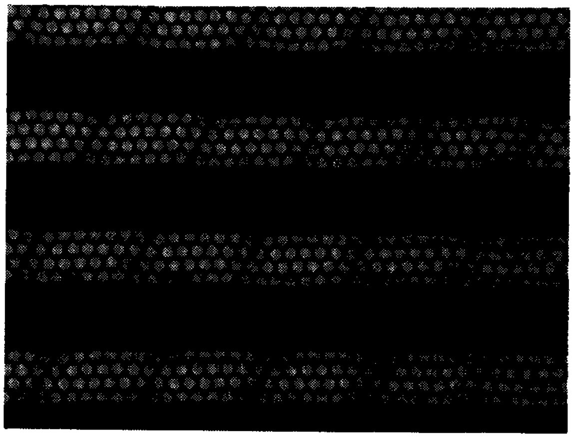

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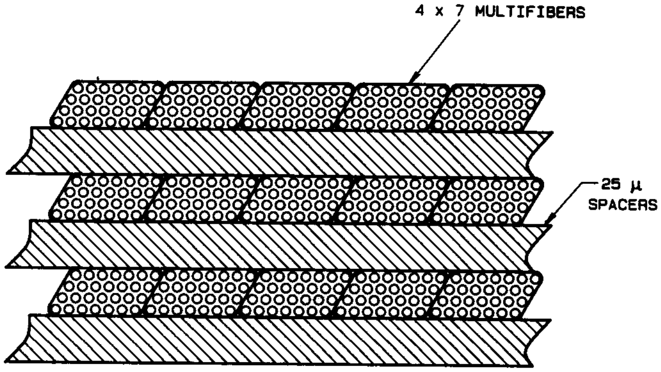

Fig. 10. Skip-layer-wound cable.

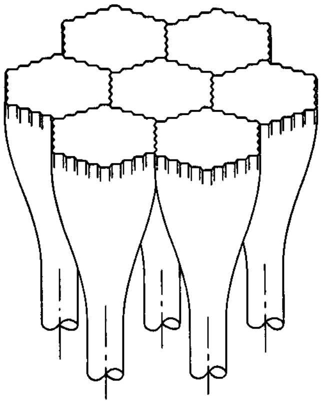

Fig. 11. Fused, leached cable.

TABLE V. Relative standing of factors influencing resolving power of fiber optic image cables.

Approach	Fiber Core Size (Microns)	Fiber Misalignment	Fixed Pattern Noise
Skip-Layer Wound Multifiber	5	Low	Moderate
Leachable Bundles	8 - 10	Near Zero	Low

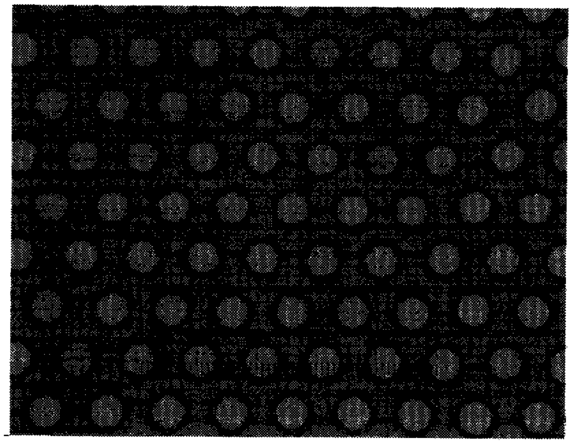

Fig. 12. Fiber arrangement in the current fused cable.

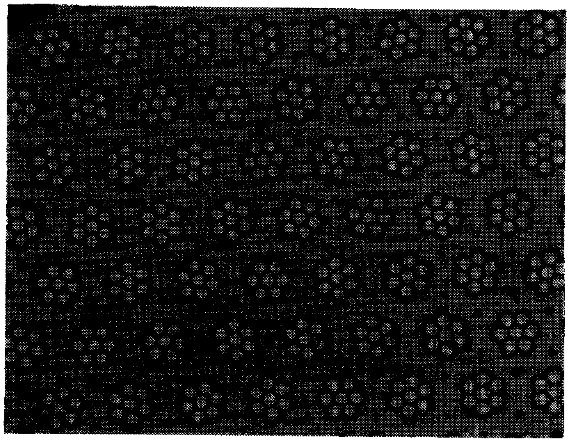

Fig. 13. Fiber arrangement in hepta (rosette) design fused cable.

of meeting the unique precision fiber drawing needs of the FOHMD program. Heathway was awarded the contract to design and build a tower (of approximately 2.1 m in height) that uses a closed-loop feedback system to maintain bundle and fiber size. For purposes of this program the tower is required to draw fibers to within ±3 μm of set point. During acceptance test runs at Heathway this requirement was met.

Fiber size and deviation from set point will be measured by a dual-axis laser micrometer (a custom-designed unit built by Lasermike Inc.). SFO has developed software for the micrometer processor that accurately computes the size of hexagonally shaped multifibers independent of its rotational orientation in the scanning working area of the micrometer.

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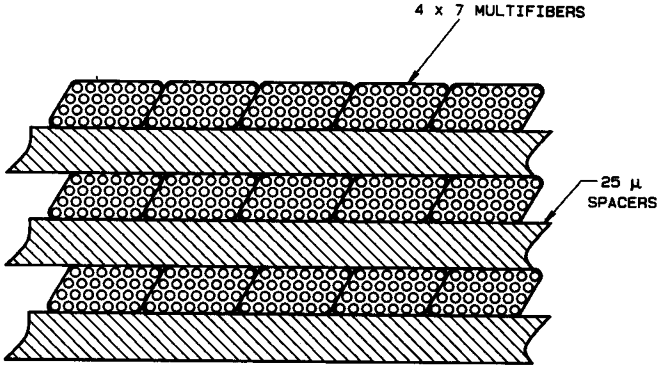

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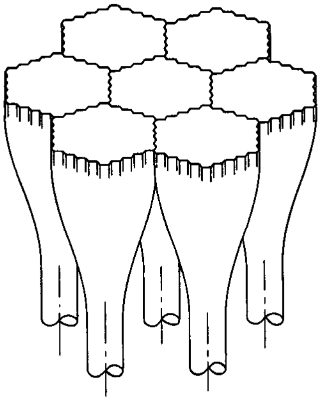

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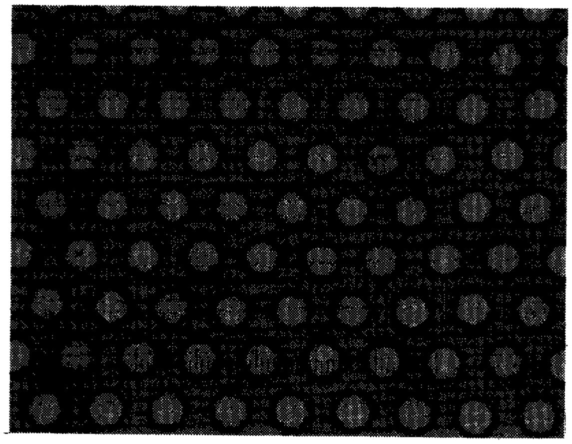

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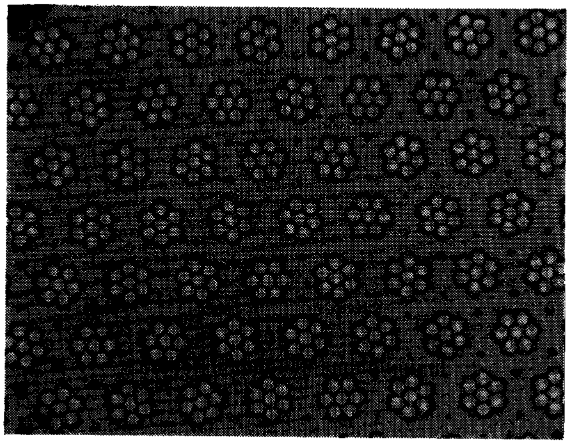

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