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"Electronic TV pick-up and film scanning techniques"

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Trends in T.V. Camera design, by S.L. Tan, Philips Research Labs.

Talking about future developments of colour television broadcast camera's is in fact talking about the future of television broadcast itself. In recent years broadcasters haveshown a growing interest in the production of programmes based on immediacy.
This clear trend to an immediate confrontation of the viewers with the happening will be even more pronounced in the future as a consequence of the introduction of new competitive systems for the mass distribution of audio visual programmes such as the video-disc and cassette.
As these systems are preeminently suitable for the distribution of programmes of a non volatile nature, television broadcast will find its strength in the production of programmes in which immediacy is essential.
As a consequence future broadcast camera's should be designed specifically to have improved flexibility and reliability to meet the operational demands.

To realise such a camera many proposals have been made during the past years for one tube camera systems,
all of them based on dot sequential colour separation.
As long as the resolving power of pick up devices is marginal and an excess is not to be expected in the near future these systems will fail to meet the demands of broadcast quality programme production.
New pick up devices have been introduced some of them having interesting features but without rejecting innovations the three tube colour camera using three lead oxide pick up tubes seems to be the best,

It is interesting to notice that the success of such a camera is not as much based on specific excellent features of lead oxide tubes but on the unique combination of many of the more or less marginal properties, sufficient, but also necessary to meet the severe demands of broadcast quality camera's.
That this assumption is valid is illustrated by the many corrections and enhancing methods introduced during the years to improve camera performance, such as alignment, dynamic focus, contour and colour enhancement, biaslighting, anti comet tail etc.

It is obvious that all these necessary measures have complicated the originally so simple three leadoxide tube colour camera.
For many years in the Philips Research Laboratories work has been done to overcome these problems.
In 1968 the 5/8" hybrid mini Plumbicon was introduced in the LDK 13 hand held camera. Experiences with this have confronted us with the following problems.

a. Production of the tube was difficult
b. The 2-watt kathode produced too much heat in the small camera.
c. The resolution in the picture centre was reduced compared to that of an all magnetic tube.
d. The electron optical anode lens was used over its whole area resulting in geometric distortion in the corners of the picture and as a consequence registration problems.

Some of these problems have been succesfully solved in a tube of a new electron optical design using a diode gun, an accelerating lens and a unique head construction (see J.H.T. van Roosmalen, "New Possibilities for the design of Plumbicon Tubes" IEEE Trans. on Electr. Devices Vol. ED-18 Number 11, Nov. 1971, pp. 1087 - 1093).
Built on the experiences with this tube a few years ago Jan van Roosmalen of our laboratory has designed a new tube, using 0,6 W kathode and of much simpler construction, having very interesting features for the camera design.

5/8" extended head hybrid Plumbicon

Tube properties	Consequences for the camera design
A Electrostatic focus therefore:	
1. uniform resolution over the whole picture area	1. no dynamic focus necessary
2. no rotation of deflection because of focussing	2. fixed position of deflection coil (stability)
3. low weight : tube + coil 80 gr.	3. simple mech. contruction (stability)
4. small volume tube + coil ± 80 cc.	4. small compact camera.

B Diode Gun current hunting diafragm therefore:

1. fixed beam current	1. fixed beam current and focussing
2. no cross over (low beam resistance	2. reduced lag, no bias lighting needed
3. reduced demands on vacuum	

C Accelerating lens

1. small spot diameter	1. excellent resolution
2. separation of focus and deflection space	2. low demands on electrode potentials
3. long equipotential space in the 1st anode	3. no alignment necessary

D Anode lens + extended head construction

1. evaporated anode , therefore max. diameter of anode mesh lens resulting in low corner effects.	1. very small damping on deflecting field, excellent geometry, simple registration.
2. mesh output in the head	2. no spurious signals induced by the deflection field, resulting in stable black level.
3. reproducable mesh target distance and position	3. excellent by matched geometric simple regristration
4. robust mesh construction	4. reduced microphony
5. target output in the window low target cap (2 à 3 pF)	5. improved S/N ratio.

The next aim looked for is the realisation of a better, shorter and simpler tube.

Better : for improved registration, resolution and sensitivity

Shorter : for improved mechanical stability and better camera ergonomy

Simpler : for reduction of production costs.

To obtain the three demands simultaneously use will be made of LSI circuits and non volatile memories to correct for static errors in the tube.

Real time correction will be added to maintain stable operation.

Signal processing

The fast progress in technology of digital LSI circuits and memories offers new possibilities to improve camera performance. Interframe video signal processing can be used to reduce noise; cross colour etc. It is also of interest to realise the fact that system standards such as PAL NTSC and Secam only applies for the transmission part of the colour television system.

In the studio as well as at the receiving end any deviating standard can be used to improve picture quality. In the studio we can think of camera's working in for example a 625 lines / 25 Hertz non interlaced system, followed by signal processing and terminated with standard conversion to normal PAL standard (625 lines /25 Hertz 2:1 interlaced). It is expected for such a camera to result in an improved resolution.

All solid state pick up devices

CTD and CID image sensors have intrigued camera designers.

Next to the attractive properties however many essential problems have to be solved in order to meet the severe demands of broadcast quality camera's. It is worth while to notice that the advantages are closely related with the read out mechanism whilst the problems originate from the light sensitive properties of the Si-diodes.

An interesting property of these devices is that there is no real practical limitation of the resolving power. The more elements the better resolution. This property combined with the exact discrete read out might offer a preeminently interesting solution for a one device colour camera.

Conclusion

Television broadcasting practice shows clear tendencies to programmes based on immediacy. The competition of new media for mass distribution of audio visual programmes will enforce these trends.

The three tube camera eventually combined with LSI circuits can meet these demands for the future. Improved pick up tubes will solve many problems inherent with 3-tube camera systems. Within the system standards of today still many improvements can be implemented to obtain better picture quality. CTD sensors show interesting possibilities especially for one device colour camera's but is not expected within the next 5 or 10 years.

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"Present Status of CCD Image Sensors for Solid State TV Cameras"

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I. Introduction

Solid State Image Sensors, such as the charge coupled devices (CCD)[1], will clearly impact the future of television cameras--monochrome and color, broadcast and non-broadcast -- since they offer major potential advantages in physical characteristics and performance.

This paper will review the basic principles and technologies of CCD image sensors, present the state-of-the-art in charge coupled imaging, and discuss the prospects for practical applications.[2]

II. The Basic CCD Shift Register

1. MOS Capacitor: Since a CCD is physically just a linear array of closely-spaced MOS capacitors, it is important to understand the MOS capacitor and how the surface potential, ϕ_s (the potential at the Si-SiO_2 interface relative to the potential in the bulk of the silicon), depends upon the type of charge at this interface. Fig. 1 shows a cross-sectional view of an MOS capacitor with a p-type silicon substrate. When a positive step voltage is applied to the gate of such a structure, the majority carriers, holes, are repelled and respond within the dielectric relaxation time. This results in a depletion region of negatively-charged acceptor states near the surface of the silicon. Just after the step voltage is applied to the gate, the silicon conduction band at the surface is well below the equilibrium Fermi level and electrons, the minority carriers, will tend to gather there. However, it takes a rather long period of time (from 1 to 100 sec) for thermally-generated minority carriers to collect in sufficient numbers to return the system to thermal equilibrium. When they do gather at the surface, they form an inversion layer (which resides within 100Å of the interface) and tend to reduce the surface potential, ϕ_s. When ϕ_s goes to ϕ_{smin}, no more charge can be gathered or stored in the potential well. Thus, the following fluid model of the MOS capacitor emerges: a potential well for minority carriers can be created by applying a step voltage to the gate and this well will take a relatively long period of time to accumulate charge thermally. For times much shorter than this thermal relaxation time, a potential well exists at the surface, and the depth of this well can be altered by changing the gate voltage. When minority carriers are introduced as signal charge in the potential well, they tend to reduce the depth of the well according to Q_{sig}/C_{well} so they tend to fill up the well much like fluid in a container.

2. Basic Charge-Transfer Action: A three-phase CCD is just a line of these MOS capacitors spaced very close together with every third one connected to the same gate, or clock voltage as shown in Fig. 2a. If a higher positive voltage is applied to the ϕ_1 clock line than ϕ_2 and ϕ_3, the surface potential variation along the interface will be similar to Fig. 2b. If the device is illuminated by light, charge will accumulate in these wells. Charge can also be introduced electrically at one end of the line of capacitors from a source diffusion controlled by an input gate. To transfer this charge to the right to the position under the ϕ_2 electrodes, a positive voltage is applied to the ϕ_2 line. The potential well there initially goes deeper than that under a ϕ_1 electrode, which is storing charge, and the charge tends to move over under the ϕ_2 electrodes. Clearly, the capacitors have to be close enough so that the depletion layers overlap strongly, and the surface potential in the gap region is a smooth transition from the one region to the other. Next, the positive voltage on the ϕ_1 line is removed to a small positive DC level, enough to maintain a small depletion region, increasing the surface potential under the ϕ_1 gates in the process. Now the ϕ_2 wells are deeper, and any charge remaining under ϕ_1 gates spills into the ϕ_2 wells. The charge, at least most of it, now resides one-third of a stage to the right under ϕ_2 gates. The charge is prevented from moving to the left by the barrier under the ϕ_3 gates. A similar process moves it from ϕ_2 to ϕ_3 and then from ϕ_3 to ϕ_1. After one complete cycle of a given clock voltage, the charge pattern moves one stage (three gates) to the right. No significant amount of thermal charge accumulates in a particular well because it is continually being swept out by the charge transfer action. The charge being transferred is eventually transferred into a reversed-biased drain diffusion and from there it is returned to the substrate. The charging current required once each cycle to maintain the drain diffusion as a fixed potential can be measured to determine the signal magnitude (current-sensing) or a re-settable floating diffusion or floating gate which controls the potential of a MOSFET gate can be employed (voltage-sensing).

3. Limitations on Speed and Efficiency: Clearly, 100% of the charge cannot move instantaneously from one potential well to another. Also, some of the charge gets trapped in fast interface states at each site and cannot move at all. Therefore, in a given clock period, not quite all of the charge is transferred from one well to the next. The fraction of the total that is transferred (per gate) is called the transfer efficiency, η. The fraction left behind is the loss per transfer, or transfer inefficiency, denoted ε, so that $\eta + \varepsilon = 1$. Because η determines how many transfers can be made before the signal is seriously distorted and delayed, it is a very important figure of merit for a CCD. If a single charge pulse with initial amplitude P_o is transferred down a CCD register, after n transfers the amplitude P_n will be:

$$P_n = P_o \eta^n \approx P_o e^{-n\varepsilon} \qquad \text{(for small } \varepsilon\text{)} \qquad (1)$$

Clearly, ε must be very small if a large number of transfers are required. If we allow an $n\varepsilon$ product of 0.1, an overall loss of 10%, then a 3ϕ, 330 stage shift register requires $\varepsilon \leq 10^{-4}$, or a transfer efficiency of 99.99%. The maximum achievable value for η is limited by how fast the free charge can transfer between adjacent gates and how much of the charge gets trapped at each gate location by fast interface states.

Several physical mechanisms cause charge motion from one potential well to an adjacent deeper well, including charge repulsion, thermal diffusion, and drift under the influence of fringing fields induced by the gate voltages. The rate of transfer depends mainly upon the gate length along the direction of charge movement and to a lesser degree upon substrate doping, clock waveforms and other structural parameters. Computer simulations indicate that conventional surface channel devices with 10 μm gate lengths are capable of efficient operation at 5-10 MHz. Experimental devices with 7.5 μm gate lengths have been operated at 20 MHz with transfer inefficiencies of 10^{-3}.

Interface states can generally fill much faster than they can empty and, thus, retain some of the signal charge and release it into trailing signal packets. This type of loss can be minimized by continually propagating a small zero-level charge, or "fat zero", through the device which tends to keep the surface states filled so that they do not have to be filled by the signal charge. This transfer loss due to interface state trapping and the subsequent requirement for fat zero charge can both be eliminated if the potential well is moved away from the $Si-SiO_2$ interface. This is done in the buried channel (or peristaltic) CCD by including a thin surface layer of conductivity type opposite to that of the substrate.

III. CCD Image Sensors

1. Background: The apparent advantages of an all solid-state, self-scanned (as opposed to electron beam scanned) image sensor, or television pick-up device, include smaller size, lower power, all solid-state ruggedness, longer lifetime, lower operating voltage--in general, freedom from the problems associated with a vacuum tube and electron beam device. Prior to the advent of charge transfer devices, all self-scanned imagers incorporated some type of X-Y addressing scheme in which vertical and horizontal conductor lines (either metal or diffusions) were used to address an array of some type of photosensitive elements such as photoconductors or photodiodes. An element was addressed when pulses applied to the horizontal lines and vertical lines coincided at that location. However, the X-Y addressing scheme faces certain fundamental problems which limit its usefulness. These include the large capacitance associated with read-out lines and the non-uniform coupling of clocks to the output at each element.

The charge transfer concept, originally introduced in 1969, has made possible a new scheme for constructing self-scanned imagers. Rather than sequentially addressing each photosensitive element by a switch, the signal charge is shifted in series along a line of MOS capacitors which form a CCD register from the point of photogeneration to a single output amplifier.(Fig.3) The charge is shifted from one low-capacitance element to another in sequence and therefore the sensitivity is not limited by high output capacitance regardless of the number of elements. In addition, clock feedthrough occurs only at the output stage at a frequency of twice the video pass band which is easily filtered or otherwise removed. Thus the basic problems of X-Y addressing are not present in a charge-coupled imager (CCI). The CCI has some of its own problems, however, the main one being transfer inefficiency tending to degrade modulated signals and limiting the resolution of the device. In addition, close spacing between adjacent MOS capacitor plates must be achieved. This imposes special processing tolerances and/or structures which are not presently made using 'standard' technology.

2. Line Scanners: The optical input can be introduced from the top of the substrate through the spaces between non-transparent metal gates or by transmitting the optical input through transparent gates such as thin polysilicon. An alternative approach consists of thinning the substrate in the

optically sensitive area and applying the optical input from the back side of the substrate. Let us assume now that an optical input is applied to such a CCD register while the clock voltages are adjusted so that one potential well is created at each stage along the CCD channel. The photogenerated charge will collect in these wells during the optical integration time. At the end of the integration time, the accumulated charge packets representing the integrated optical input are shifted down the CCI register and detected by a single output amplifier. To prevent smearing of the image, the optical integration time should be much larger than the total time required to transfer the detected image from the CCD line sensor. Since all charge elements are amplified by the same amplifier, nonuniformities--usually a problem in optical arrays in which each sensor element uses a separate amplifier--are avoided. Since there is no direct coupling of the clock voltages to the charge signal in the CCD channel, the clock pick-up is limited only to a single output stage. In addition, since only the clock frequency, which is outside of the video bandpass, is used in CCD transfer, clock pick-up is not the problem as it is in X-Y scanned arrays. This type of device in which the CCD register serves to store the photogenerated charge during integration and shift it to the output register during read-out is called an illuminated register device.

Another scheme for constructing line sensors involves a linear array of separate sensors (photocapacitors or photo diodes) which continuously integrate the optical input. The signal is periodically transferred into a CCD register which is used for read-out only and is not illuminated. It is essentially an analogue parallel-to-series converter, with time-integrated optical input and electrical output.

3. Area Arrays: One way of implementing an area charge-coupled imager (CCI) is illustrated in Fig. 4. This array can be visualized as a parallel array of the previously described linear arrays whose outputs are transferred in parallel into a single output register. The operation of this CCI is as follows. Once every frame time the charge signal detected by the photosensor array is transferred into the vertical CCD channels, which are not photosensitive. Then, the entire detected image is shifted down in unison by clock A and transferred into the output register one (horizontal) line at a time. The horizontal lines are then transferred out from the output register by the high frequency clock B before the next horizontal line is shifted in. This approach to area imaging is called the interline system.

Another frame transfer CCI that does not require separate photosensors is shown in Fig. 5. This system is composed of three functional parts: the photosensitive array, a temporary storage array, and the output register. The optical image is detected by the photosensitive array and is transferred into the temporary storage array by clocks A and B, during the vertical blanking time. From there it is shifted down one horizontal line at a time into the output register and transferred out by the high speed clock C.

4. Performance Limitations of CCIs: The main limitation of CCIs is the degradation of signal modulation which can occur after the large number of transfers required. The severity of this problem depends upon the overall

loss Nε, where N is the total number of transfers and ε is the inefficiency per transfer. Figure 6 shows a plot of MTF due to transfer inefficiency against line pairs per picture element with εN as a parameter. Since the overall system MTF is the product of all the individual MTFs, the maximum permissible value for εN will depend upon other components of the system. εN values of unity should be satisfactory in most cases. Another source of signal modulation degradation in a CCI is the sampling process which occurs when the modulated light intensity input is detected by sampling the intensity at discrete points.

To be compatible with standard TV scanning, an imager must be capable of interlace--the reading of every other horizontal line in successive field times. In a charge-coupled imager, interlacing actually increases the resolution of the device. It is accomplished by collecting the photogenerated charge under alternate-phase electrodes in alternate fields. This effectively doubles the spatial sampling frequency and correspondingly reduces the distortion introduced by fold-over effects.

As in the silicon vidicon, light overloads tend to spread laterally, or "bloom". However, anti-blooming structures are possible in CCIs and have been demonstrated experimentally. In addition, the CCD is inherently a low noise device and therefore has the capability of providing high dynamic range and very sensitive performance.

5. The Present Status of Charge-Coupled Imaging: The first production charge-coupled device was announced in March 1973 exactly three years after the introduction of the CCD. In this device, built by Fairchild Camera and Instrument Corporation, the 500 photoelements are read out alternately by two 250-stage, three-phase, buried channel devices with polysilicon gates with undoped gaps. Subsequently, a number of companies have built line sensors of various lengths. The largest CCD line array to date is Fairchild's 1728 stage device.

Development of area arrays has also been rapid. Bell Telephone Laboratories announced the first one--a 64 x 106 vertical transfer system with separate store having an overall size of 106 x 128. Three of these devices have subsequently been utilized to build a color CCD camera. The light is split by a prism and the different color components are imaged on the three devices. Bell Labs recently announced a larger area array, a 475 x 496 device using the three-phase, triple polysilicon gating structure.

Fairchild has been the first to announce a commerically available area array product--a 100 x 100 buried channel array using interline transfer. It employs a two-phase gating system and displays a dynamic range of 1000 to 1. It now makes a 190 x 244 element device and also reported on a 380 x 488 area array.

The highest-resolution, commercially-available charge-coupled image sensor is the RCA SID 51232. This device is a 512 x 320 element area imager of the frame-transfer type. Operating with 2:1 vertical frame interlace mode, the SID 51232 imager is capable of full vertical TV resolution. The photosensitive area of this device is comprised of surface-channel CCD registers that are normally operated in the parallel "accumulation mode" of blooming control. The additional feature of this type of operation is the electronically adjustable gamma that can be used to extend the dynamic range of the imager. The serial horizontal-line read-out of this imager is accomplished by a buried-channel CCD register. Thus, a full horizontal resolution of 320 contiguous horizontal picture elements is achieved. In other words, the horizontal resolution of this image sensor corresponds to an MTF of 0.6 for 240 TV lines per picture height.

6. Conclusions: The charge-coupling concept presents an alternative technique for achieving all solid-state, self-scanned imaging. It is free from the clock feedthrough, high output capacitance, and uniformity problems of X-Y addressed systems. The CCI is inherently a low noise device with low output capacitance and appears capable of more sensitive operation than the silicon vidicon. A cooled buried channel device may exceed I-SIT performance. Thus, it is almost certain that CCI's will ultimately replace camera tubes in broadcast television cameras.

Presently commercially available devices are already suitable for industrial, military, space, and other applications, where light weight, small size, low power consumption, reliability, long life and extreme resistance to physical shock are of paramount importance. They do not, however, meet the broadcaster's overriding requirement for pictures of extremely high quality. Here, technological improvements are required until CCI's will be able to match the excellent performance with respect to resolution, uniform response free of blemishes, spectral response, presently offered by conventional camera tubes, and at a competitive price.

The ultimate factor affecting the eventual success of charge-coupled imagers in the market place depends upon the ability of manufacturers to fabricate chips with acceptable performance, in sizes large enough to satisfy resolution requirements, and with yields high enough to permit low cost.

Perhaps the inherent performance advantages of charge coupled imagers will motivate the industry to develop the large chip technology required. If so, CCI's should become within 1-3 years quite prevalent in closed circuit and medium quality TV systems where the resolution of devices already constructed in the laboratory should be sufficient. However, sensors capable of meeting normal broadcast standards require at least 483 x 644 (USA) or 585 x 760 (PAL), significantly greater than any existing device. The charge-coupled concept is capable, in principle, of achieving this resolution. If CCI's are to be used in broadcast applications, significant advances in large area silicon technology are required.

References:

1. W. S. Boyle and G. E. Smith, "Charge-Coupled Semiconductor Devices," Bell System Tech. J. 49, 587, 1970.

2. For comprehensive review of this topic see J. E. Carnes, "Charge-Coupled Imaging: State of the Art," Proc. 1973 ESSDERC, pp. 83-107, 1974.

C-4

Television Zoom Lenses in Modular Construction

by Karl Macher

1. Introduction

Because variable focal length lenses for television cameras can be used in a wide variety of conditions, a number of special systems are necessary. The economy of the design and manufacture of these lenses is endangered due to the high costs involved.

In planning this study, the object was to devise alternatives to determine the technical feasibility of keeping development and manufacturing costs within reasonable limits without sacrificing the variety of uses.

The solution to the problem has been sought in modular construction.

Many compromises in the design of zoom lenses have to be accepted when considering the use of these lenses for television cameras (Fig. 1).

1. Studio lenses	Large relative aperture, minimum ratio of 10:1 together with very short minimum object distance and large field angle.
2. Lenses for large studios, theatres, sports halls etc.	Large relative aperture, minimum ratio of 15:1; where the shortest focal length is equal to the format diagonal, short minimum object distance - less than 1 metre.
3. Lenses for outside broadcasts, e.g. sports grounds and stadiums where there is a long distance from camera to subject	Large relative aperture, large focal length ratio, including a long focal length and a minimum object distance of less than 5 metres.

Considering the design in conjunction with camera use the following is expected of the new systems:

Corrections for the glasspath in the beamsplitting system that separates the red green and blue images, low weight and ease of operation.

2. Research in the field of Gaussian Theory

A zoom lens is made up of several function groups or modules with different functions (Fig. 2).

2.1 The Front Element or Front Module

This is the group of lenses and lens elements facing the subject. To focus precisely at varying distances these elements have to be moved along the optical axis. The range of variation of focal length, the maximum relative aperture of the system and the minimum object distance all influence the optical design of the front module, its construction and dimensions.

2.2 The Variator or Zoom Module

This consists of two completely separate function groups moveable on the optical axis. The front group produces a fixed intermediate image which, according to the variator position, is shifted into a further intermediate image. To increase the focal length range, a second variator or zoom module can be used.

2.3 The Basic Lens

This basic lens accepts, as object, the intermediate image produced by the variator and projects it on to the image plane. Its design and construction is dependent upon the required aperture and the back focal distance, t, which has to be exceptionally long in colour television cameras to accommodate the beamsplitter.

2.4 In addition to the relative aperture, the range of focal lengths and the minimum object distance, the dimensions of a zoom system are dependent upon the position of the entrance pupil. The result is the position of the diaphragm and the distribution of the power of the individual function groups.

By changing the individual function groups or modules, the following modifications are possible:-

1. Variation of the range of focal lengths.
2. Shift of the range of focal lengths.
3. Shift of the range of focal lengths.
4. Alteration of the relative aperture.

The illustrations 2a and 3 with performance data for TV Vario Systems show this.

(Fig 2a) The addition of a range extender, added as a further module, basic lens system of 3 modules, causes a shift on the focal length range and an influence of the relative aperture.
Exchange of the basic lens results in two further variations of the zoom lens.
It is therefore possible, to produce from six optical modules, four zoom lenses, each with different specifications.

A more elegant solution would be the use of "flip-in" optical components or range extenders; in this way the optical system would remain on the camera.

One should not forget to mention that the use of "flip-in" range extenders will cause a sudden change of relative aperture and focal length.

In Fig. 3 twelve TV-Vario lenses - zoom lenses - are detailed which are constructed from nine modules. If each of the twelve lenses were to be manufactured as a separate item, fourty-two individual groups would be necessary. The advantage of modular construction is obviOUs

3. TV Zoom Lenses of Modular Construction

To make the study easier, six systems with a 30:1 zoom range have been selected for illustration.

Aperture	Focal length range mm	Horizontal angle of view at E = ∞	Minimum object distance M	Format size mm x mm
1,7...5,1	12,5... 375	53°... $1,9^\circ$	0,40	9,6 x 12,8
1,7...5,1	16 ... 480	43°... $1,5^\circ$	0,85	9,6 x 12,8
1,7...5,1	26 ... 800	27°... $0,92^\circ$	3,00	9,6 x 12,8
2,1...6,3	16 ... 480	56°... 2°	0,40	12,8 x 17,1
2,1...6,3	20 ... 600	45°... $1,6^\circ$	0,85	12,8 x 17,1
2,1...6,3	33 ... 1000	29°... $0,98^\circ$	3,00	12,8 x 17,1

These six systems are constructed from seven optical modules. With standard methods of construction, twenty-four groups would be required.

The seven optical modules are:-

Front group I (Wide Angle)
Front group II (Normal)
Front group III (Tele)

Variator I (15:1 ratio)
Variator II (2:1 ratio)

Basic lens III (Relative aperture f/1.7 Format 9.6 mm x 12.1mm
Basic lens IV (Relative aperture f/2.1 Format 12.8 mm x 17.1mm

4. Study in the field of Seidel Theory

The Seidel co-efficients at the refractive surfaces, respectively their sum, can be used to judge the influence of the single function groups upon the imaging error. The known Seidel formulae were analytically transformed and specially re-worked for zoom lenses. It is therefore possible to see easily the influence of the function groups on the spherical abberation, coma, astigmatism, geometric distortion, longitudinal chromatic abberation and transverse chromatic abberation. The Petzval sum is known to be focal length invariant and is not shown. This is proved with an example of a modular system, that of the TV Variogon 20 - 600 mm f/2.1. The system consists of four modules with a total of seven optical function groups (Fig. 4). The front group, the first moving group, the second moving group, the fixed intermediate group, the third moving group, the fourth moving group and the basic lens. To show this clearly, only the interactions of the function groups on the spherical abberation are shown in the illustration (Fig. 5).

It is evident that the error contribution of the function group 7 is constant and independent of focal length. This is related to the mode of construction of the lens, because behind the moving groups lay independent paths. Therefore it is clear that not only the moving groups 2, 3,5 and 6 but additionally the fixed front element show various error contributions. The error contributions, in groups 1 and 2 particularly are considerably high, even so the sum total of the error contributions of all modules is quite small.

Each optical function group shows typical variations in abberations with change of focal length. When focusing, conventionally, with the complete front group (L_1-L_8) onto very close subjects, the distortions or abberations are so extreme as to endanger the imaging quality at long focal lengths. By uniform distribution of the abberations onto all components of the front group, the imaging performance against linear magnification is almost invariant when focusing with the negative front portion (L_1-L_3).

As an example three further variants of the modular construction (Fig. 6) in relation to the Seidel abberation theory are presented.

1. TV Variogon 33-1000 mm f/2.1 for the format 12.8 mm x 17.1 mm with 1 1/4" picture tubes. — The system is the result of exchanging the front group of the TV Variogon 20-600 mm f/2.1.

2. TV Variogon 16-480 mm f/2.1 for the format 12.8 mm x 17.1 mm with 1 1/4" picture tubes. — The system is the result of exchanging the front group of the TV Variogon 20-600 mm f/2.1.

3. TV Variogon 16-480 mm f/1.7 for the format 9.6 mm x 12.8 mm with 1" picture tubes. — The system is the result of exchanging the basic lens of the TV Variogon 20-600 mm f/2.1.

When interchanging modules or function groups, the characteristic features of the abberations' interference have to be maintained. The optical construction is a result of this knowledge. The specific interaction of the different modules on the spherical abberation is seen in Fig. 7 and can easily be compared.

5. The Modular Construction

When the individual optical modules - be they front element, basic lens or zoom module - are exchanged, the result is new systems with different performance data. These are:-

5.1 Front elements with different refractive - optical-power

The focal length range is shifted whilst relative aperture and image circle diameter illumination remains constant. The result is different object-side field angles for each initial focal length and longest focal length.

5.2 Basic lenses with different refractive - optical - power

The focal length range is shifted , the relative aperture and image circle diameter are changed proportionally with the same factor as the shift. The object-side field angle of each of the initial and longest focal lengths remains constant.

5.3 Application of a second variator

An increase in the focal length range will result. In the first variator, the focal length variation is primarilly influenced by the first moveable function group; in the second variator, primarilly by the second function group, meaning the four moveable function groups of the complete system. The refractive power distribution and the optical design are a result of the demand for compact construction and optimum image quality.

5.4 Relative Aperture

The relative aperture specified, f/2.1 (f/1.7), remains constant for the first ten factors, i.e. ten times the initial focal length for all six systems. Thereafter it decreases proportionally to f/6.3 (f 5.1) with increase of focal length.
If the relative aperture is reduced to f/6.3 by means of the diaphragm (f/5.1) it will remain constant over the entire focal length range.
For apertures between full aperture and the aperture at the longest focal length the relative aperture remains constant up to the corresponding

It is of course possible to keep the relative aperture equal over the whole zoom range, but this would result in an excessive front diameter and unacceptable weight.

5.5 Minimum Object Distance

Focusing onto close objects is achieved by axial movement of part of the front group or module. The resultant image quality has already been described. The possibility of close focusing was, in each case, designed in accordance with the range of application and is dependent on the design of the front group as a whole. In order to focus from infinity to less than one metre with front groups I and II, it is necessary to use the front negative portion. Whilst with front group III focus is achieved with a positive front portion.

The same effect can be achieved, as has been shown in practice, by focusing with the second part of the front group provided there is enough air space between the two parts of the front group.

The dimension of the object fields and the linear magnifications are a result of minimum object distances attainable by the three front groups