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E I N D H O V E N   U N I V E R S I T Y   O F   T E C H N O L O G Y

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TRANSMISSION OF FM-MODULATED AUDIOSIGNALS IN THE 87.5 - 108 MHz BROADCAST BAND OVER A FIBER OPTIC SYSTEM

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SUMMARY

This investigation examined the possibility of transmitting 16 audio-signals in the FM broadcast band with a fiber optic system; a description of the fiber optic system, with its main components, is given.
In the FM band the signal to noise ratio and the signal to intermodulation ratio were measured; both figures are just too small to meet the requirements of the Dutch PTT.
Some signal to noise ratio measurements in the audio band for single tone modulation were made and from them the signal to noise ratio data for an audio spectrum was derived.
Experiments with CAI systems showed that coupling the fiber optic system directly to a head end gives a good quality signal. Coupling it to the end terminal of a subscriber line gives a slight reduction in quality.

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1. INTRODUCTION

Analog transmission of video or audio modulated signals over fiber optic systems was believed to have a poor performance. Due to the high frequencies involved in such systems the only possible light source is a laser diode (LD) and, until recently, these devices were very nonlinear. FM systems are less sensitive to nonlinearities than AM systems. If many signals within a relatively small frequency band are transmitted, these signals disturb each other. This interference is a result of the intermodulation due to non-linearities. Nowadays, lasers with very low distortion factors have been reported [1]. This fact suggested that transmission of several audio signals via the FM broadcast band 87.5 - 108 MHz was possible with acceptable performance. A fiber optic system was constructed for a practical evaluation of this suggestion. Several measurements of FM signals transmitted over this system were carried out. The modulation was taken in accordance with the CCIR recommendations 412-1 and 450 [2]. The emphasis time constant was 50 μs (corresponding to an emphasis break frequency of 3.18 kHz), whereas the maximum frequency deviation was 75 kHz. For stereophonic transmission the pilot tone system was chosen with a subcarrier frequency of 38 kHz.

2. DESCRIPTION OF THE FIBER OPTIC SYSTEM

The fiber optic system is schematically depicted in Fig. 1. The input signal is supplied to the drive circuit. This circuit modulates the laser current proportionally to the input signal.

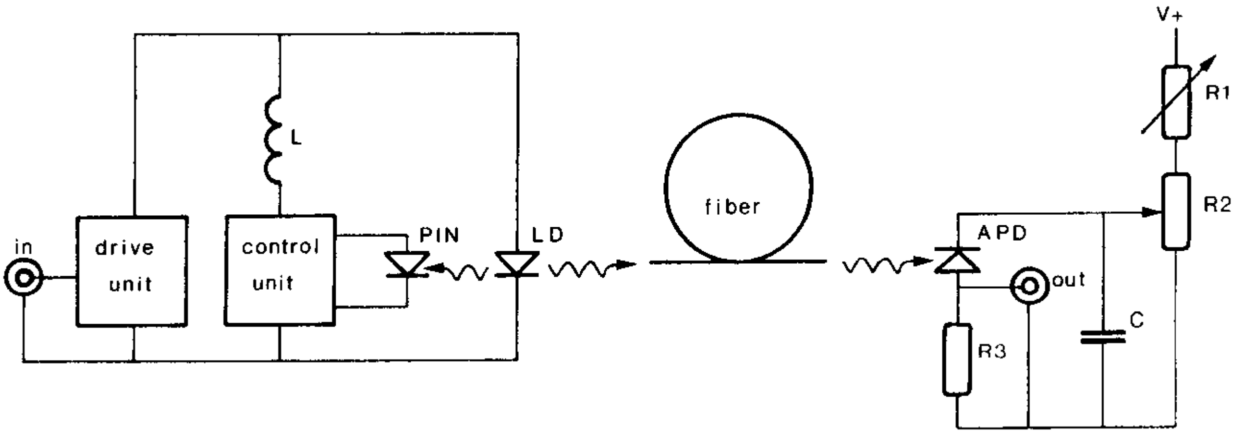

Fig. 1 : The fiber optic system

A small part of the laser light is coupled to a PIN photodiode whose current acts as the input signal of a control unit. This unit controls the bias current of the LD such that the mean optical output power is stabilized.

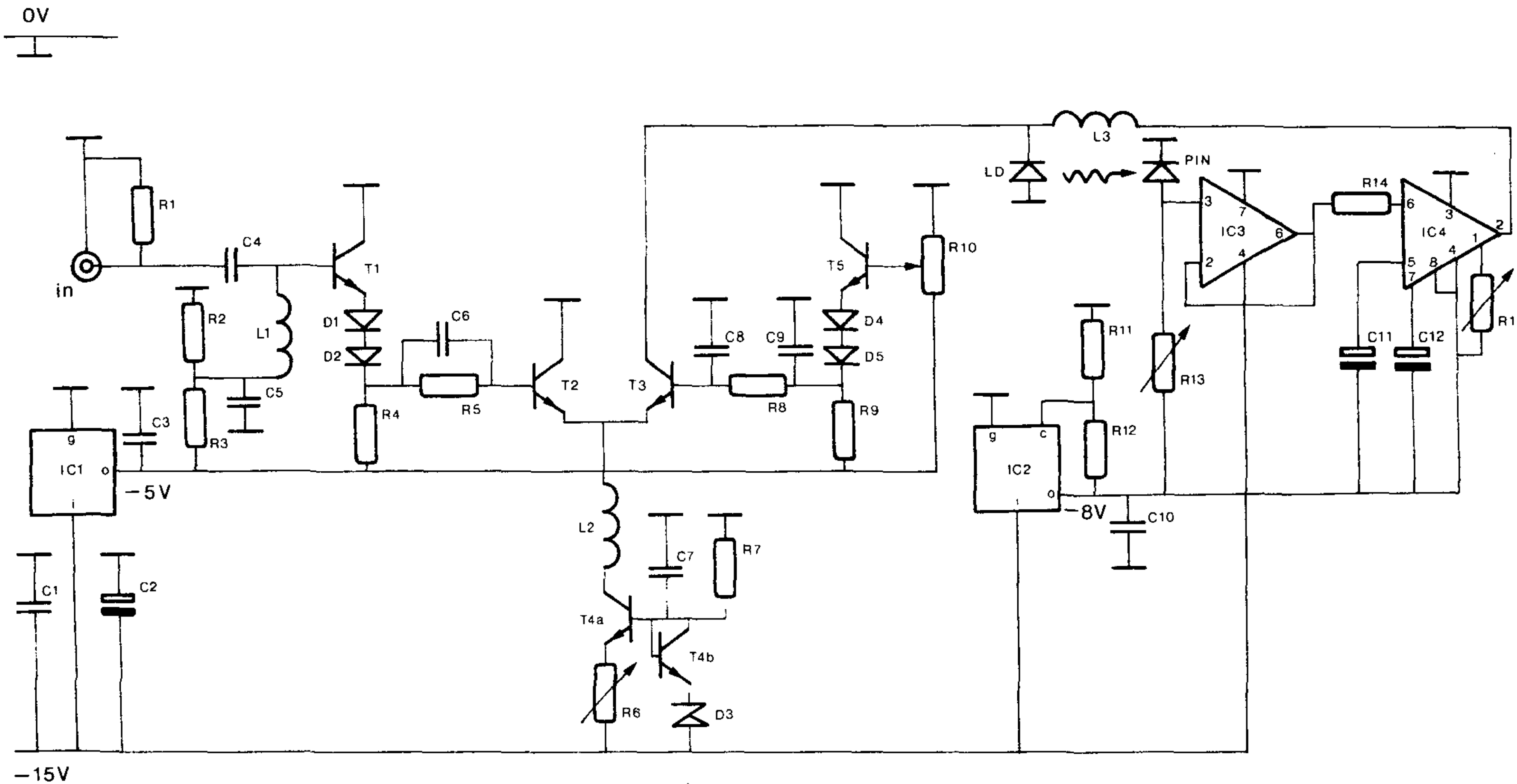

Fig. 2 : Laser drive and control unit

Most of the LD output power is coupled into a graded index fiber. At the receiving end the output light power of the fiber is coupled to an APD. Apart from the bias resistances R_1 and R_2, this APD has a load resistance R_3 of 5.6 kΩ. This latter resistance prevents a DC overload of the input circuit of the measuring equipment to occur. The effective load of the APD is determined by the input impedance of the measuring equipment, or FM receiver, which has to be connected in parallel to R_3 and normally has a value of 50 Ω.

2.1 The drive and control unit

Detailed schemes for the drive and control unit are given in Fig. 2. The heart of the drive consists of a long tailed pair, preceded by a level converter and an emitter follower. The control unit consists of a voltage follower IC3 and a voltage controlled current source IC4. (For a detailed components list, see the Appendix).

2.2 The laser diode

The light source in the fiber optic system is a laser diode of the DH type (Hitachi HLP 1600). The output power versus current characteristic of this LD is given in Fig. 3. For a long lifetime of the LD, it is recommended that the maximum current does not exceed the threshold current (I_{th}) plus 25 mA. Therefore, the laser is biased at I_{th} plus 12.5 mA, which corresponds to a mean laser power of 3 mW. The maximum signal current shall not exceed 12.5 mA. Signals in FM/FDM cable distribution systems have an rms value of ca. 80 dBμV per signal. Such a signal supplied to the drive input gives a maximum current change of 0.75 mA. If systems are considered with a maximum of 16 programs, the maximum modulating current will be 12 mA.
The optical spectrum of the laser, as measured with a Fabry-Perot interferometer, is given in Fig. 4. The interferometer was a Burleigh RC 110 with a minimum resolvable bandwidth of 62.5 pm. Emission takes place in almost a single transverse and longitudinal mode at a wavelength of 831 nm. In Table 1, the most important laser data is summarized.

Table I : Summary of the laser data

type	emitting wavelength	threshold current I_{th}	bias current	mean output power
Hitachi HLP 1600	831 nm	62.5 mA	75 mA	3 mW

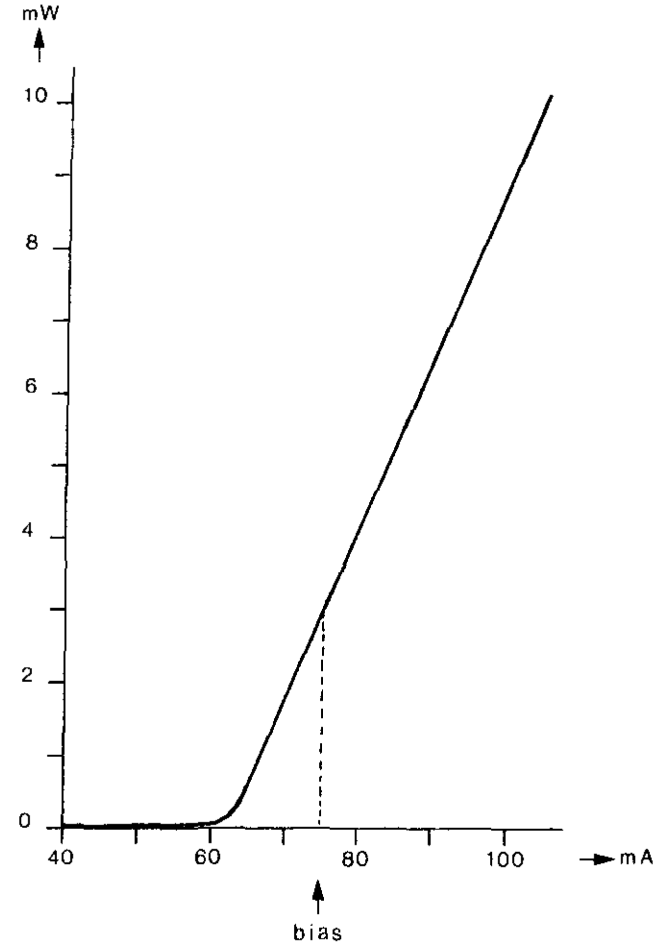

Fig. 3 : The light power versus current characteristic of the LD

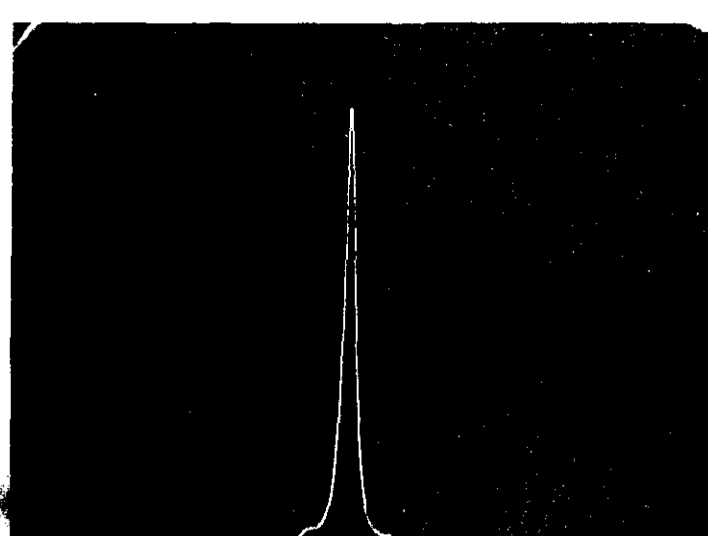

Fig. 4 : The optical output spectrum of the laser as measured with a Fabry - Perot interferometer.
Hor. scale 0.5 nm/div.

At the given bias of 75 mA (see Table I) of the LD the distortion figures as collected in Table II were measured.

Table II : Distortion figures of the LD Hitachi HLP 1600				
	Signal level at the input of the drive unit			
	75	80	85	dBµV
2nd harm. dist.	-47	-44	-40	dB
3rd harm. dist.	-65	-60	-53	dB

2.3 The fiber

The optical waveguide is a Corning graded index fiber. In Table III the data for this fiber is given.

Table III : The data of the fiber						
type	length	attenuation at 830 nm.	num. ap.	core diam.	cladded diam.	coated diam.
Corning 5101	1100 m	5 dB	.225	62.5 µm	125 µm	138 µm

2.4 The photodiode

The photodiode is an APD. The measured ratio of the ionization coefficients of holes and electrons is k = 0.019 [3]. The mean multiplication gain was given the value of ten. A summary of the APD data is given in Table IV.

Table IV : Summary of the APD data					
type	mean gain G	responsitivity at 830 nm and G = 10	ionization ratio k	excess noise factor at G = 10	dark current
RCA C30902E	10	6.5 A/W	0.019	2.05	12×10^{-9}A

For the excess noise factor see [4].

3. MEASUREMENTS

In order to evaluate the performance of FM/FDM distribution over the fiber optic system specified in the foregoing chapter, some measurements were carried out. These measurements are subdivided into three categories:

- signal to intermodulation ratio (SIR) measurements in the FM broadcast band 87.5 - 108 MHz,
- signal to noise ratio (SNR) measurements both in the FM broadcast band and in the audio band at tone modulation,
- measurements in CAI systems*.

In Section 4 the relation between the SNR in the FM band and the SNR in the audio band will be verified theoretically. Moreover, in the same section, SNR figures for an audio signal will be derived from the SNR figures for single tone modulation.

3.1 Intermodulation

Three carrier waves of respectively 92.6, 96.8 and 98.9 MHz were supplied to the drive input. Fig. 5 and Fig. 6 show the spectrum of the laser intensity at respectively 80 and 85 dBμV input level. The horizontal scale is linear and extends from 87 to 107 MHz.

From these pictures the signal to intermodulation ratios** of Table V can be easily verified.

Table V : SIR figures

Input level	SIR
80 dBμV	56 dB
85 dBμV	45 dB

---

* CAI is the abbreviation of the Dutch "Centrale Antenne Inrichting", which means: the system for the local distribution via cable of central received radio and TV signals.

** The SIR has not been measured as indicated in [7], as then the result is dependent on the specific carrier frequencies of the stations. As SIR we took the ratio of the carrier wave amplitudes and the amplitude of the largest intermodulation product that is found in the FM band.

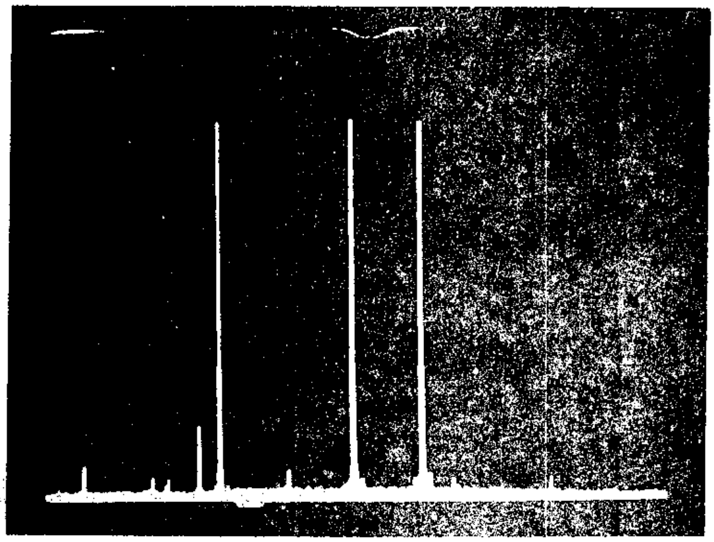

Fig. 5 : The laser intensity spectrum with spectral lines at 92.6, 96.8 and 98.9 MHz. Horizontal scale 87 - 107 MHz (linear).
Vert. scale 10 dB/div.
Input level 80 dBμV per carrier.

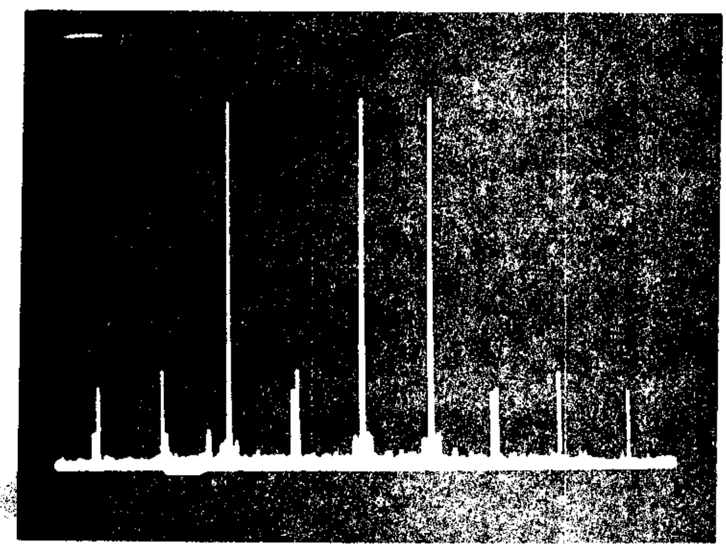

Fig. 6 : As Figure 5 except that the input level is now 85 dBμV per carrier.

N.B. The spectral lines at 88.2 and 91.9 MHz were signals picked up directly from local broadcasting stations. They did not disappear when the test signals were removed.

3.2 Signal to noise ratios

It is common practice to specify the noise in the FM band with a bandwidth equal to the message bandwidth [5, 6]. For audio this means a bandwidth of 15 kHz. At 80 dBμV input level was measured

$$SNR_{HF} = 63 \text{ dB (15 kHz bandwidth)} \quad .$$

If the noise specified has a bandwidth of 200 kHz as is required in [7],this SNR value becomes

SNR_{HF} = 52 dB (200 kHz bandwidth) .

The output level over 50 Ω was 60 dBμV at the given gain of ten of the APD. This output level can be changed easily by adjusting the APD gain.

In the instance of the tone modulation measurements, a carrier in the 87.5 - 108 MHz band was frequency modulated by a single sine wave of 1 kHz and supplied to the input of the fiber optic system. The amplitude of this 1 kHz tone was adjusted so that the maximum frequency deviation of the modulated signal became 75 kHz. An FM receiver with stereo decoder (Philips NL 1320/1303) was connected to the output of the APD circuit. The deemphasis time constant of this receiver is 50 μs, corresponding to a deemphasis break frequency of 3.18 kHz, which is in accordance with CCIR recommendation 412-1.

A stereophonic transmitter was not available, therefore, the stereophonic noise measurements were simulated by means of modulation with a weak 19 kHz sine wave so that the stereo decoder was activated. The measured low frequency SNR values are given in Table VI.

Table VI : The SNR values in the audio band

	Input level					
	50	60	70	80	90	dBμV
mono : flat filter	55	64	69	70	70	dB
psophometer filter	51	60	68	70	70	dB
stereo : flat filter	34	43	51	59	62	dB
psophometer filter	28	37	46	57	60	dB

The psophometer filter measurements were carried out with the CCITT-C filter. From the figures in Table VI it is clear that the noise limit of the receiver itself is 70 dB.

3.3 Measurements in CAI systems

Two experiments in CAI systems were carried out. The first one consisted of connecting the fiber optic system of Fig. 1 to a subscriber terminal of a CAI with 16 programs. In Table VII the precise frequencies and identifications of the stations are given, whilst the spectrum as measured with a spectrum analyzer is depicted in Fig. 7. In this figure the frequency range 84 - 104

MHz was recorded. The level of the signals was around 75 dBμV (after 20 dB amplification). Fig. 8 gives a schematical representation of the spectrum. In Fig. 9 and Fig. 10, the frequency interval 96.5 - 101.5 MHz of the recorded spectrum is extended, respectively, before and after the fiber optic system. From these figures, it follows that the SIR after the fiber optic system is 48 dB to 54 dB, whereas the SNR_{HF} at this point is about 55 dB. The figures for the subscriber signal were resp. 56 dB and 63 dB (measured with a bandwidth of 10 kHz). In the stereophonic mode a small increase of the noise was audible after insertion of the fiber optic system. This increase was estimated to be some 2 or 3 dB.

Table VII : Frequency and station identification of the first CAI

Frequency [MHz]	Station identification code
88.5	RTL
89.5	RTB 2
90.2	RTB 3
90.8	BRT 1
91.3	BRT 2
92.1	BRT 3
93.1	H 1
94.2	H 4
95.3	H 3
96.2	WDR 1
97.6	WDR 2
98.2	WDR 3
100.2	BFBS
100.8	ROZ
101.5	H 2
102.6	SROB

During the second experiment the system was connected to the head end of a CAI. This system involves 12 programs whose precise frequencies and identifications are given in Table VIII, whereas the spectrum is schematically given in Fig. 11. At input levels of 80 dBμV per signal, even in the stereophonic case, no increase of noise was audible after insertion of the fiber optic system. Of course, the SIR and SNR_{HF} values of the latter system are larger than those of the 16 program subscriber signal, although no exact data is available.

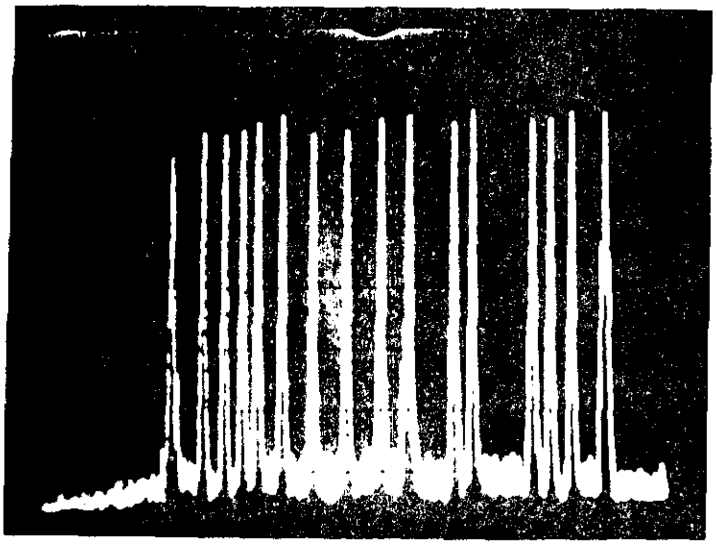

Fig. 7 : The spectrum of the subscriber signal in a CAI involving 16 programs.
Hor. scale 84 - 104 MHz.
Vert. scale 10 dB/div.
Measured with a bandwidth of 30 kHz.

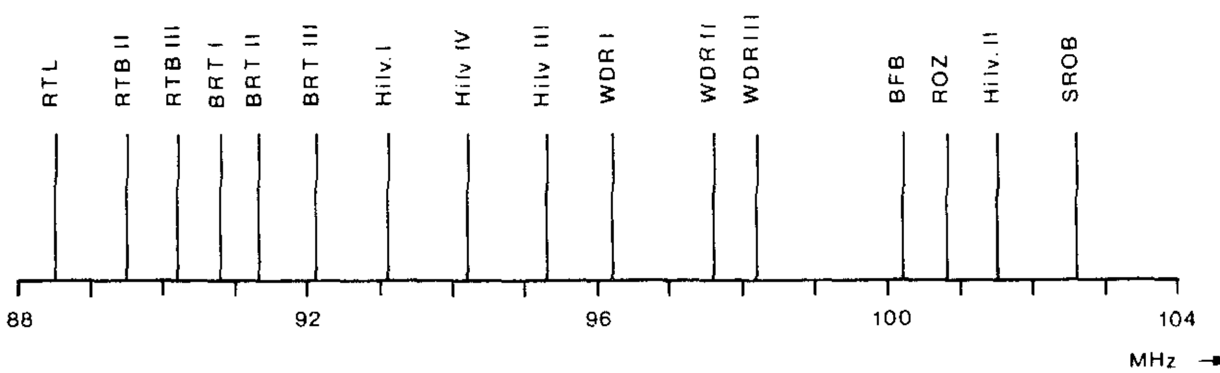

Fig. 8 : *Schematical spectral representation and identification of the 16 stations in the CAI.*

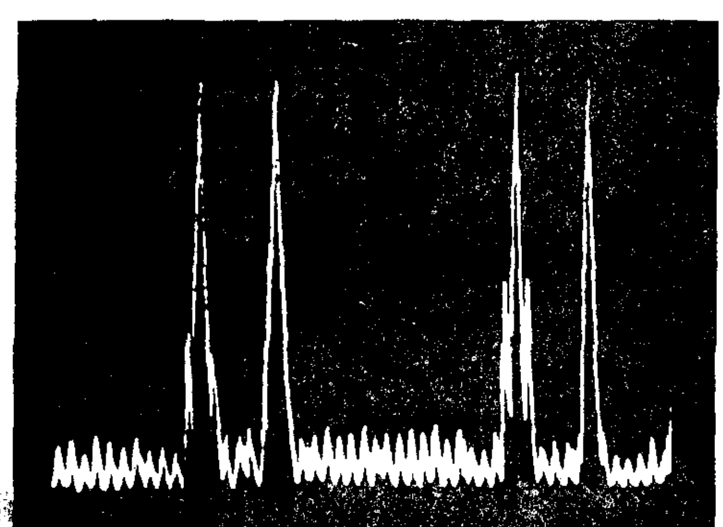

Fig. 9 : Extended frequency interval 96.5 - 101.5 MHz of Fig. 7.
Measured with a bandwidth of 10 kHz.

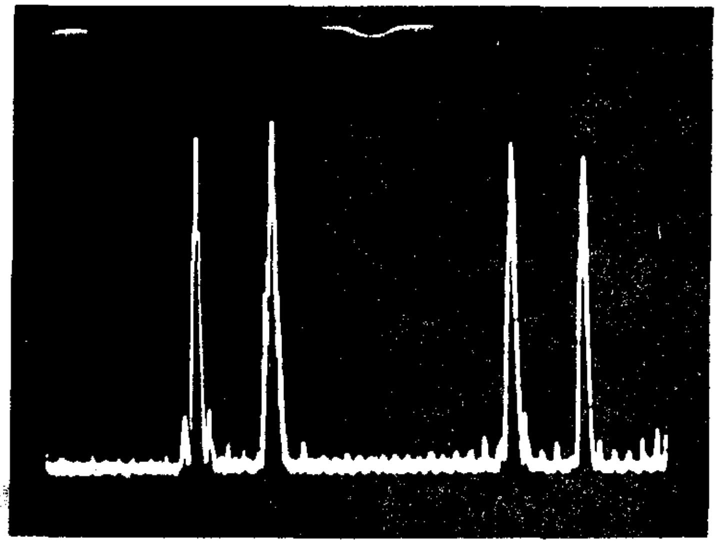

Figure 10 : As Figure 9, but at the end of the fiber optic system.

Table VIII : Frequency and station identification of the second CAI	
Frequency [MHz]	Station identification code
89.9	BRT 3
90.9	ROZ
91.9	SROB
92.6	H 1
93.2	RTB 1
95.6	RTB 2
96.1	RTB 3
96.8	H 3
97.5	BRT 2
98.9	H 4
99.9	BRT 1
100.9	BFBS

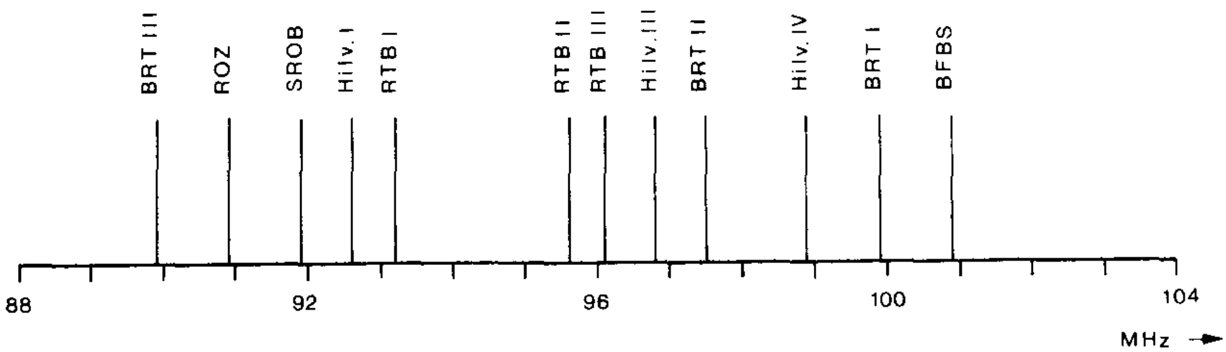

Fig. 11 : Spectrum and identification of the 12 stations system.

4. THEORETICAL CONSIDERATIONS OF THE MEASURED SNR_{LF} AND ITS RELATION TO SNR_{LF} FOR AUDIO SIGNALS

4.1 SNR_{LF} versus SNR_{HF} for tone modulation

The SNR_{LF} measurements, as described in Section 3, have been well defined. For the LF signal measurements, the carrier was frequency modulated by a single tone of 1 kHz. In the case of the monophonic noise measurements, the carrier was unmodulated, whereas for the stereophonic noise measurements the carrier was modulated by a single weak 19 kHz tone so that the stereo decoder was activated. In order to understand the relationship between the various SNR values, it is important to know the measuring conditions.

Firstly, a monophonic system without emphasis is considered. When the bandpass noise is assumed to be white and Gaussian, then above the threshold, the SNR_{LF} can be deduced from the SNR_{HF}, as follows [6]:

$$SNR_{LF} = 3\left(\frac{f_\Delta}{W}\right)^2 \frac{\overline{x^2(t)}}{|x(t)|^2_{max}} SNR_{HF} \quad , \qquad (1)$$

where

f_Δ = the maximum frequency deviation,

W = the message bandwidth,

$x(t)$ = the information signal or message.

and the SNR_{HF} is measured with a bandwidth W.

When a monophonic system with emphasis is considered, the righthand side of Equation (1) has to be multiplied by a factor [6],

$$R = \frac{(W/f_e)^3}{3\{W/f_e - \arctan\,(W/f_e)\}} \quad , \qquad (2)$$

where f_e is the deemphasis break frequency.

For a sine wave, the crestfactor

$$\frac{\sqrt{\overline{x^2(t)}}}{|x(t)|_{max}}$$

becomes $1/\sqrt{2}$. If the numerical values of the various system parameters are substituted in (1) and (2), it follows that the SNR_{HF} has to be increased by 25.9 dB in order to arrive at the SNR_{LF}. This gain consists of 15.7 dB detection gain and 10.2 dB deemphasis gain. When comparing this rule to the measurements of Section 3, at an input level of 50 dBμV, the SNR_{HF} will be 33 dB. This means that, theoretically, the SNR_{LF} is 58.9 dB, whereas it is 55 dB in fact. It can be assumed that the difference arose from the noise of the receiver itself (implying a receiver noise figure of 18 dB).

Next, the stereophonic measurements are considered. The signal power is not changed with respect to the monophonic case, because the $(L-R)$ signal is not operating, but the noise increases drastically as shown by the analysis in the sequel. In the $(L+R)$ signal the noise power equals that in the monophonic case and is [5]:

$$\overline{n_1^2} = \frac{\eta f_e^3}{S_R} \left\{ \frac{W}{f_e} - \arctan\left(\frac{W}{f_e}\right) \right\} \quad , \tag{3}$$

where:

S_R = the received signal power,

η = the single sided spectral density of the bandpass noise at the receiver input.

The spectral density of the noise in the $(L-R)$ signal is called $G_{n2}(f)$. The deemphasis characteristic is given in Fig. 12a and the FM postdetection idealized bandpass filter characteristic for the $(L-R)$ signal is depicted in Fig. 12b, together with the FM postdetection noise spectral density [5]

$$G_n(f) = \frac{\eta f^2}{2S_R} \quad . \tag{4}$$

It follows that the low pass spectral density of the $(L-R)$ noise becomes

$$\begin{aligned} G_{n2}(f) &= |H_d(f)|^2 \{G_n(f_{sc}-f) + G_n(f_{sc}+f)\} \\ &= |H_d(f)|^2 \frac{\eta}{2S_R} \{(f_{sc}-f)^2 + (f_{sc}+f)^2\} \quad , \quad |f| \leqslant W \quad , \end{aligned} \tag{5}$$

where

$H_d(f)$ = the deemphasis characteristic,
f_{sc} = the subcarrier frequency of the DSBSC modulated *(L-R)* signal.

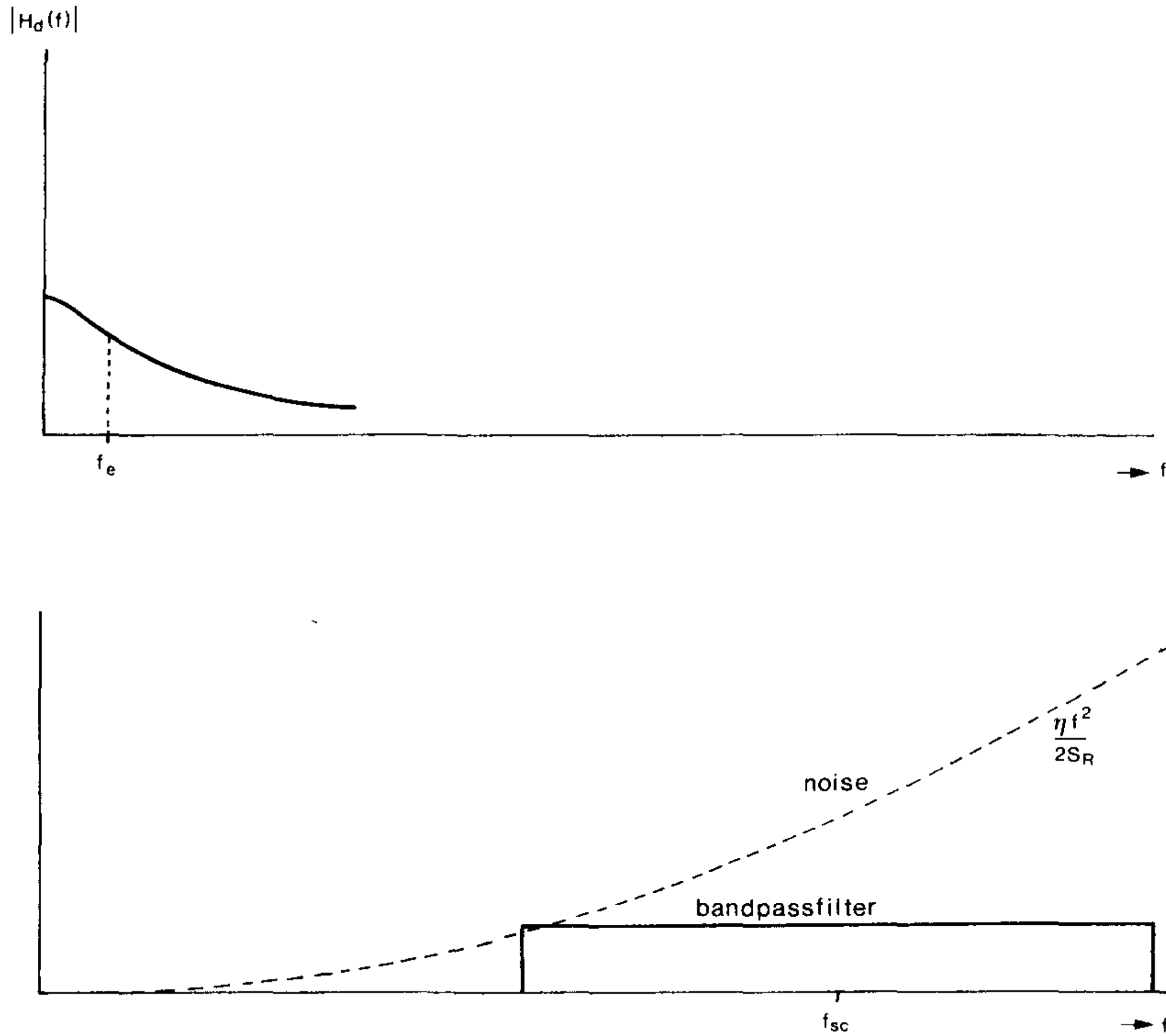

Fig. 12 : a) The deemphasis characteristic.
b) The postdetection noise spectral density and idealized bandpassfilter characteristic for the *(L-R)* signal.

Equation (5) means that the mean power of the *(L-R)* noise equals

$$\overline{n_2^{\,2}} = 2\int_0^W G_{n2}(f)\,df = \frac{2\eta}{S_R}\int_0^W \frac{f^2 + f_{sc}^{\,2}}{1+\left(\frac{f}{f_e}\right)^2}\,df =$$

$$= \frac{2\eta f_e^{\,3}}{S_R}\left\{\frac{W}{f_e} + \frac{f_{sc}^{\,2} - f_e^{\,2}}{f_e^{\,2}}\arctan\left(\frac{W}{f_e}\right)\right\} . \tag{6}$$

Numerical evaluation of (3) and (6) with the given system parameters yields

$$\overline{n_1^{\,2}} = 3.36\,\frac{\eta f_e^{\,3}}{S_R} , \tag{7a}$$

$$\overline{n_2^{\,2}} = 396\,\frac{\eta f_e^{\,3}}{S_R} . \tag{7b}$$

Forming the L signal and the R signal, the $(L+R)$ and $(L-R)$ signals have to be added and subtracted respectively; also, the noise contributions $n_1(t)$ and $n_2(t)$ likewise. But $\overline{n_1^{\,2}(t)}$ is negligible with respect to $\overline{n_2^{\,2}(t)}$, therefore the noise in both the R and L channel are determined by $n_2(t)$. As far as the measurements of the tone modulation are concerned, the SNR_{LF} for stereophonic transmission is degraded by a factor $\overline{n_1^{\,2}}/\overline{n_2^{\,2}}$ with respect to the monophonic case, i.e.

$$\frac{(SNR_{LF})_{stereo}}{(SNR_{LF})_{mono}} = \frac{3.36}{396} = 0.00851 = -\ 20.7\ \mathrm{dB} . \tag{8}$$

The results of the measurements (see Table VI) show a difference of 21 dB in those cases where the noise contributed by the receiver is not dominant and the filtering is flat. This difference agrees with (8).

4.2 SNR_{LF} versus SNR_{HF} for the audio spectrum

In the case of tone modulation, as described in the foregoing paragraph, the 1 kHz tone is not affected by the emphasis circuits; this is in contrast with an audio spectrum. In the transmitter, frequencies above f_e are pre-emphasized; however, the maximum frequency deviation is bounded to 75 kHz, so that the mean power of the signal has to be decreased. In doing so the advantage of emphasis is partially cancelled. This effect reduces the SNR_{LF}. For the sake of deriving this reduction, it is assumed that the spectrum of the audio signal is given by

$$G_a(f) = \frac{G_o}{1 + \left(\frac{f}{f_e}\right)^2} , \qquad |f| \leqslant W . \tag{9}$$

The reduction factor takes the simple form [6]

$$K = \frac{f_e}{W} \arctan \left(\frac{W}{f_e} \right) \quad . \tag{10}$$

Numerical evaluation gives a reduction of 5.4 dB in the monophonic transmission case. There is yet another reduction caused by the fact that the crestfactor for audio signals is smaller than for a sine wave. A reasonable value seems to be 1/4, reducing SNR_{LF} by a factor 1/16 or 12 dB and in respect of the tone modulation 9 dB. Therefore, in monophonic transmission there is a total decrease in SNR_{LF} of 14.4 dB when compared with tone modulation.

For stereophonic transmission, there are other effects. First of all, there is the power of the 19 kHz pilot tone; then, it is assumed that the reduction in SNR_{LF} caused by this effect is 1 dB. Secondly, apart from the *(L+R)* signal in baseband, the *(L-R)* signal is DSBSC modulated at 38 kHz and the power of this intermediate signal is

$$\overline{x_b^{\,2}(t)} = \overline{\{x_{L+R}(t) + x_{L-R}(t) \,.\, \cos(2\pi f_{sc} t)\}^2} =$$

$$= \overline{x_{L+R}^{\,2}(t)} + \frac{1}{2}\, \overline{x_{L-R}^{\,2}(t)} \quad . \tag{11}$$

Assuming that the *L* and *R* signal have a covariance equal to zero, it is found that $\overline{x_b^{\,2}(t)}$ is unity when:

$$\overline{x_L^{\,2}(t)} = \overline{x_R^{\,2}(t)} = \frac{1}{3} \quad . \tag{12}$$

For monophonic reception this means that the received LF power becomes:

$$\overline{\{x_L(t) + x_R(t)\}^2} = \frac{2}{3} = -\ 1.8 \text{ dB} \tag{13}$$

and for stereophonic reception the *LF* power is

$$\overline{\{2x_R(t)\}^2} = \overline{\{2x_L(t)\}^2} = \frac{4}{3} = 1.2 \text{ dB} \quad . \tag{14}$$

In conclusion, the reduction matrix, with respect to the sine wave calculations, is given in Table IX for the various combinations of monophonic versus stereophonic transmitting and receiving.

Table IX : Reduction in SNR_{LF} with respect to the sine wave figures			
		transmitting	
		mono	stereo
receiving	mono	-14.4 dB	-17.2 dB
	stereo	-	-14.2 dB

These figures exclude the 20.7 dB difference between monophonic and stereophonic reception due to the increase of noise to the *(L-R)* signal, as derived in Paragraph 4.1. Considering the SNR_{LF} for an audio spectrum when the nominal input level is 80 dBµV and excluding the noise contribution of the receiver, then, for stereophonic transmission these figures are as given in Table X.

Table X : SNR_{LF} for an audio spectrum for stereophonic transmission; input level 80 dBµV.	
mono : flat filter	72 dB
stereo : flat filter	54 dB

These figures include the 20.7 dB decrease in SNR_{LF} between the stereophonic and monophonic case.

5. CONCLUSION AND FINAL REMARKS

Distribution of 16 programs in the FM broadcast band via fiber optic systems appeared to be possible; however, the resulting SIR of 56 dB and SNR_{HF} of 52 dB that were measured in a bandwidth of 200 kHz, were slightly too small to meet the requirements of [7]. Audio experiments when the fiber optic system was inserted at the end of the subscriber line of a CAI confirmed this. If the system was coupled directly to a head end, the quality of the audio signals was very good.

It is possible to increase the SNR values by 6 dB when doubling the laser bias and modulating current at the cost of a shorter laser lifetime. Increasing the modulating current, however, increases the intermodulation.

With compensation techniques, the intermodulation can be reduced. The SIR and SNR are determined by the laser, in most cases. Perhaps, in the future, new lasers will become available, so that the requirements [7] for SNR and SIR will be met with a longer laser lifetime.

ACKNOWLEDGEMENT

The authors are greatly indebted to Ir. W. Groenewegen for giving them the opportunity to make measurements with the head end of Philips ELA/ EDS and to Dr. P. Attwood for correcting the English text.

APPENDIX

Components list drive and control unit.

R_1	50 Ω	C_1	0.1 μF
R_2	130 Ω	C_2	470 μF
R_3	365 Ω	C_3	0.01 μF
R_4	150 Ω	C_4	0.01 μF
R_5	470 Ω	C_5	0.01 μF
R_6	1k Ω	C_6	270 pF
R_7	1k2 Ω	C_7	0.01 μF
R_8	470 Ω	C_8	1200 pF
R_9	150 Ω	C_9	0.01 μF
R_{10}	1k Ω	C_{10}	0.01 μF
R_{11}	2k2 Ω	C_{11}	470 μF
R_{12}	5k6 Ω	C_{12}	470 μF
R_{13}	3M Ω		
R_{14}	1k2 Ω		
R_{15}	47 Ω		

T_1	BFR 91	L_1	0.2 mH
T_2	BFR 91	L_2	0.2 mH
T_3	BFR 91	L_3	0.2 mH
T4a/T4b	MPQ 2222		
T_5	BFR 91		

IC1	LM 320 T5	D_1	BAW 62
IC2	μA 79 MG	D_2	BAW 62
IC3	μA 741 C	D_3	1 N 829
IC4	CA 3085 AE	D_4	BAW 62
		D_5	BAW 62

LD	HLP 1600
PIN	HP 5082 - 4220.

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