Experimental study of the use of multiband acousto-optic filters for spectral encoding / decoding the optical signals

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Abstract. A prototype of the acousto-optic (AO) decoder of optical signals is created on the base of the multiband AO filter. The joint work of the decoder with the developed previously AO coder has been verified experimentally. The main qualitative and quantitate characteristics of the spectral coding and decoding by Walsh sequences of the industrial LED radiation in the near infrared range are investigated. It is shown, that in the proposed data transmission system realization Signal-to-Interference Ratio (SIR) is not less than 13 dB.

1. Introduction

At present acousto-optic tunable filters (AOTF) [1], which are based on a highly selective interaction of broadband light with a frequency tunable sound wave, are well known and widely used. The absence of moving elements and a high enough speed of tuning is an important advantage of these filters. Only in recent years [2], it was proposed to use such devices (MAOF - multiband acousto-optic filters) for multiband (but not tunable) AO filtration, which is based on multi-frequency acoustic wave excitation. It was supposed in [3] that the MAOF can become a key element of a new component base for creating optical communication systems with code division of multiple access channels (O-CDMA). In [4] the first prototype of the AO encoder for O-CDMA, which uses a bulk MAOF, based on TeO_2, has been realized and investigated experimentally.

Figure 1 shows the proposed in [3] the concept of AO decoder, that realizes the parallel decoding of spectrally encoded optical signal. The light before decoding splits into two parallel optical channels with equal power. Further, the signal filtering is carried out simultaneously by two MAOFs. Transmission spectra of the MAOFs, formed by specially synthesized RF electrical signals, correspond to two complementary Walsh sequences W_{i+} and W_{i-}. After the filtration, the radiation intensity in both channels is converted by the photodetectors PD1 and PD2 into electrical currents. The differential amplifier converts the difference between this currents into a voltage U_{out}.

In paper [3] the numerical simulation of the decoder operation was carried out and it was shown, that values of U_{out} are grouped in three well separated from each other ranges, that allowed to determine exactly which Walsh sequence was used for the signal coding.
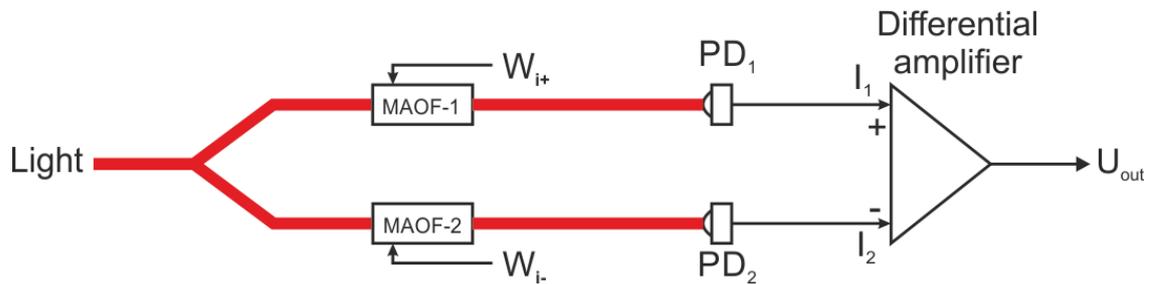
Figure 1. Schematic diagram of AO decoder proposed in [3].

In this paper the joint operation of the proposed earlier AO coder [5] and a new AO decoder prototype, functionally identical to one in [3], is studying to verify the quality of spectral coding/decoding with the use of coding Walsh sequences and a standard LED as a source of incoherent radiation.

2. Experimental setup

In designing the experimental setup, it was taken into account, that a phased verification and testing of proposed in [3] decoder circuit is appropriate and possible. At the first stage the stationary quality of spectral encoding / decoding processes was testing, whereas temporal characteristics were supposed to be studied later. A new circuit of AO decoder, proposed and realized in the experimental setup, which is shown in Figure 2, performs decoding in serial mode. Used in the previously proposed scheme, the parallel operation provides better performance, but it is sensitive to not the full identity of work in parallel channels. Systematic errors associated with the not full identity may be associated with not exact division of light in half, with the incomplete spectral identity of two MAOFs and photodetectors operation etc.

As shown in Figure 2, a new scheme uses for decoding one instead of two MAOFs. Synthesized RF electrical signals, forming multiband optical transmission function according to the selected complementary Walsh sequences in the MAOF, are fed to it sequentially. Fed to encoder MAOF RF electric signal does not change during sequential sending of these two signals on decoder MAOF. After each feeding of the electrical signal to the single encoder MAOF, the detecting of the optical signal occurs on the same photodetector, then the detected values are stored and their difference determines the value of the autocorrelation function of the expected signal. Therefore, the two circuits shown in Figures 1 and 2 have identical functionality when operating in the stationary mode.
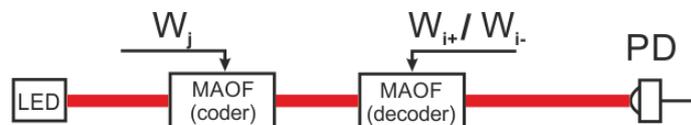
Figure 2. Schematic diagram of the experimental setup.

Figure 3 shows a block diagram of the experimental setup that realizes a schematic diagram shown in Figure 2.

The light from GaAs/GaAlAs LED TSAL6200 with 940 nm central wavelength, 100 mW power and an angle of divergence of $\pm 17^0$, after passing the collimator with a focal length F = 10 cm forms a beam with the aperture D = 10 cm, which enters the MAOF-1 (Coder) and right after it at a distance of 1 cm enters MAOF-2 (Decoder), both with the input aperture of 8 cm. The radiation, passing through the MAOF-1 and MAOF-2, is focused on the photodiode (PD). A specialized ADC module digitizes the electrical signal from the PD output. The measured data is stored, processed and displayed on a computer.

The wide non-collinear AO geometry, used in MAOF on the basis of TeO_2 single crystal, allowed to realize the following parameters: the spectral range of 900-1600 nm, the range of control frequencies 55

- 100 MHz, a spectral resolution of 2 nm at a wavelength of 1152 nm. Control electrical RF signals for both MAOFs in the range of 70-90 MHz are formed by the two-channel arbitrary waveform generator Tektronix AFG3252 and amplified by two electronic power amplifiers. To increase the signal/noise ratio the possibility of additional low-frequency (LF) modulation of RF signals with subsequent amplification and the LF filtering of the signal by Selective Nanovoltmeter type 237 was realized. Since the LED's working spectral emission band (λ = 900-980 nm) is in the invisible to the eye near-infrared range, we used a standard night vision device for the system adjustment.
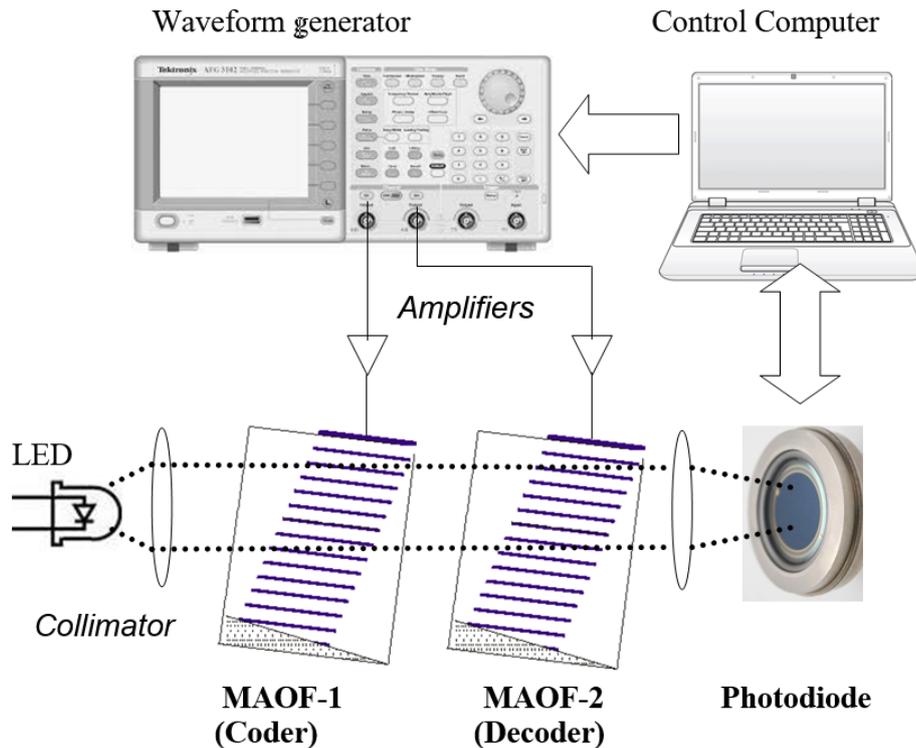

Figure 3. Block diagram of the experimental setup.

3. Experimental results and discussion

At the initial stage of the joint operation of the previously proposed encoder and a new decoder control measurements of the stationary single-band radiation spectrum were carried out at the output of encoder MAOF-1 when the decoder MAOF-2 worked in the mode of slowly tunable AOTF.

Figure 4 shows an experimental graph, obtained by the MAOF-1 in the single frequency mode, with a stationary sound wave at the frequency F = 81.0 MHz. In this case MAOF-2 operated at AOTF regime with a slowly tuning in time sound frequency F from 79.6 to 82.4 MHz. The abscissa represents the frequency of the sound, which was excited in the MAOF-2. The ordinate - optical power in relative units, digitized at the output of photodetector PD. The slight difference of the control frequencies in two MAOFs, that emerged due to technological reasons, was taken into account by software.

It can be seen that the resulting dependence of the intensity of radiation transmitted through both the MAOFs is in accordance with the transmission formula for two AO filters [3]:

$$I(\lambda) = \mathrm{sinc}^4(\Delta\lambda),$$

where $\Delta\lambda = 2\pi\Delta\mathrm{n}L(\lambda_F - \lambda)/\lambda_F^2$, Δn - the difference between the refractive indices of the ordinary and extraordinary rays in the MAOF (AOFT) material, L - the AO interaction length, $\lambda f = \lambda_F F = const$.

Figure 5 shows experimental plots obtained when MAOF operated in multi-frequency mode. These plots correspond to the spectra of two Walsh sequences with dimension 8: $W5_+$ (red graph) and $W5_-$
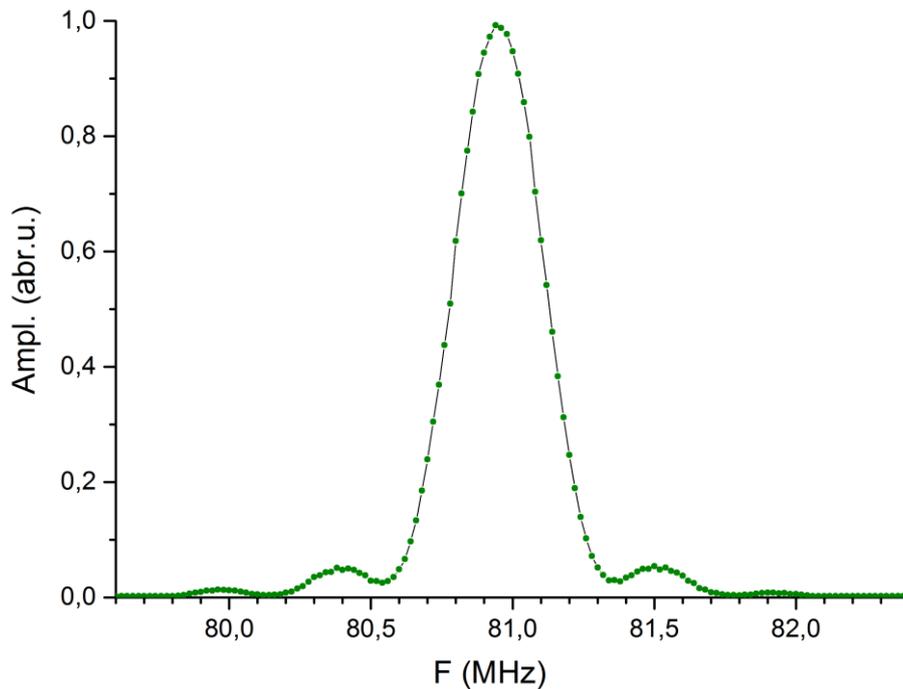
Figure 4. Transmission spectrum of the MAOF-1 at F=81.0 MHz
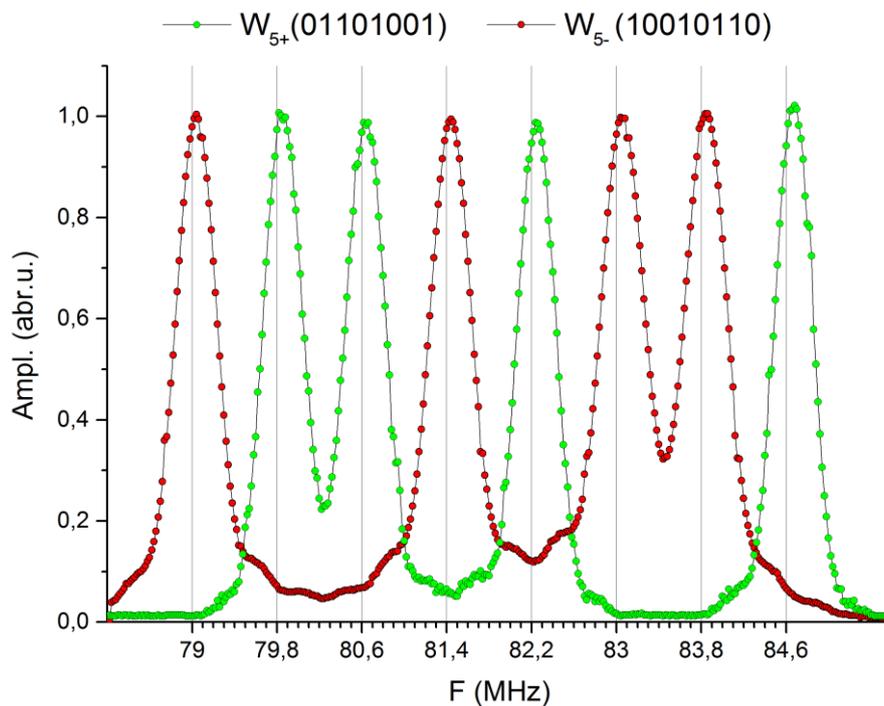
Figure 5. Transmission spectra of MAOF-1 for W_{5+} (red) and W_{5-} (green).

(green line). The abscissa represents frequencies F in the range of 78.2 to 85.4 MHz, that were fed on MAOF-2, operating in AOTF mode. The optical power in arbitrary units, measured at the output of the photodiode PD, is plotted along the ordinate axis. The spectra were formed when the MAOF was fed by the electric signal synthesized by Tektronix AFG3252. The synthesis procedure, having the purpose to

align the LED spectral emission nonuniformity, was described in [5]. Each Walsh sequence was put in correspondence with unique set of four of the eight equidistant frequencies between 79 to 84.6 with 0.8 MHz step. This step between the adjacent frequencies was chosen to be two-time Rayleigh criterion, which is enough for confident decoding, according to theoretical calculations [3]. Methods of LED spectral emission alignment, proposed in [5], allowed to reduce the nonuniformity of all spectral lines maximum amplitudes down to 5%.

Table 1 shows the correspondence between the Walsh sequences and frequencies of the control signals fed to MAOF-1 and MAOF-2 for realization any of the 10 chosen Walsh sequences with the dimension 8 $W_{i(+/-)}$ i = 1..5. Note that sequences Wi with the same index i, but different colors (red or blue), correspond to the complementary Walsh sequences.

Table 1. Correspondence between the Walsh sequences and frequencies of the control signals.

Walsh	F (MHz)							
	84.6	83.8	83.0	82.2	81.4	80.6	79.8	79.0
W_{1+}	0	1	0	1	0	1	0	1
W_{1-}	1	0	1	0	1	0	1	0
W_{2+}	0	0	1	1	0	0	1	1
W_{2-}	1	1	0	0	1	1	0	0
W_{3+}	0	1	1	0	0	1	1	0
W_{3-}	1	0	0	1	1	0	0	1
W_{4+}	0	1	0	1	1	0	1	0
W_{4-}	1	0	1	0	0	1	0	1
W_{5+}	0	1	1	0	1	0	0	1
W_{5-}	1	0	0	1	0	1	1	0

The main results of the experiment on the decoding of the optical spectra, obtained by passing an incoherent LED light through MAOF-1 (Coder) and then through MAOF-2 (Decoder), followed by the detection at PD, are shown in Table 2.

The table headings indicate labels of ten optical Walsh sequences $W_{i(+/-)}$, which have been realized in MAOF-1 in accordance with Table 1 data. The first column shows the labels of five pairs of complementary Walsh sequences W_{j+}, W_{j-}, that have been sequentially realized in MAOF-2. Besides, the five labels of Δ_j is shown below each pair (W_{j+}, W_{j-}). The data in the Δ_j line correspond to the output results of the differential amplifier shown in Figure 1. The data in the table cells (in arbitrary units) were obtained as a result of the following measurement algorithm:

1. Properly shaped and amplified electrical RF signal was fed to the MAOF-1 and generated the filter's transmission spectrum, equivalent to one of the ten of Walsh sequences, shown in Table 1.

2. The transmission spectra, equivalent to a pair of complementary Walsh sequences Wj_+, W_{j-}, was formed sequentially in MAOF-2.

3. In cells $(W_{i(+/-)}, W_{i+})$, $(W_{i(+/-)}, W_{j-})$ the digitized measurement signals from PD are shown. The light from LED passes through the MAOF-1 with the $W_{i(+/-)}$ transmission spectrum and through the MAOF-2 with W_{j+}, W_{j-} transmission spectra.

4. Line Δ_i shows the result of subtracting values in the cells $(W_{i(+/-)}, W_{i+})$ and $(W_{i(+/-)}, W_{j-})$, which is equivalent to the difference signal digitized after the differential amplifier in the decoder [3] in Figure 1. The cell data in the lines Δ_i are colored by red or blue colors, respectively, when $i = j$, and green, when $i \neq j$.

It can be seen from Table 2, that the data in the rows labelled by "Δ_i", are grouping according to the values in three spaced far apart ranges that completely coincide with the colour bands. The values of coloured in red data lie in the range from 619 to 699, in blue from -688 to -642 and in green from -35 to 30. In each of the 10 columns only one coloured data is significantly different from zero in absolute value, exactly when formed in MAOF-1 sequence $W_{i(+/-)}$ is identical or complementary to the one from pair of sequences (W_{j+}, W_{j-}), that are formed sequentially in MAOF-2.

Table 2. Main experimental results.

MAOF-2 (decoder)	MAOF-1 (coder)									
	W_{1+}	W_{1-}	W_{2+}	W_{2-}	W_{3+}	W_{3-}	W_{4+}	W_{4-}	W_{5+}	W_{5-}
W_{1+}	655	38	337	324	335	334	303	343	363	337
W_{1-}	36	691	325	322	339	326	319	327	335	362
Δ_1	619	-653	12	2	-3	8	-15	16	28	-25
W_{2+}	337	327	713	37	341	344	310	340	367	349
W_{2-}	335	337	33	700	323	326	299	331	338	352
Δ_2	12	-10	680	-663	18	18	11	9	29	-4
W_{3+}	335	337	338	332	694	44	321	339	349	355
W_{3-}	339	331	328	326	42	691	290	338	364	343
Δ_3	-4	6	10	4	652	-647	31	1	-35	12
W_{4+}	303	342	336	328	346	325	648	47	349	358
W_{4-}	319	333	343	326	336	355	43	689	354	345
Δ_4	-16	9	-7	2	10	-30	605	-642	-5	13
W_{5+}	363	327	353	323	329	358	299	343	740	43
W_{5-}	335	342	342	336	352	328	310	330	41	731
Δ_5	28	-15	11	-13	-23	30	-11	13	699	-688

The experimental results in Table 2 are fully corresponding to mathematical modeling, carried out in [3]. It can be seen that the data in the red/ blue band are concentrated in a narrow range of sufficiently large positive/negative values. So, one can see, that the signal power and, consequently, the ratio of the transmitted signal power to single-signal interference power $SIR = 10\,Log\left(699/35\right) \cong 13\ dB$.

4. Conclusions

A new prototype of multiband AO decoder, based on MAOF, is proposed and investigated experimentally. This prototype is free of systematic errors caused by the asymmetry of the two parallel optical channels in a previously introduced prototype.

A model of the transmission line (with two based on TeO_2 controlled MAOFs and industrial LED as key elements) was created for researching the optical signal spectral encoding/decoding.

It has been demonstrated, that the SIR value, calculated on the base of measured data, was about 13 dB in the transmission line realization.

References

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