AUSTRALASIAN JOURNAL OF COMBINATORICS
Volume **40** (2008), Pages 137–144

On double circulant doubly even self-dual $[72, 36, 12]$ codes and their neighbors

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Abstract

We give a classification of all double circulant doubly even self-dual $[72, 36, 12]$ codes. We also demonstrate that every double circulant doubly even self-dual $[72, 36, 12]$ code has no extremal doubly even self-dual $[72, 36, 16]$ neighbor.

1 Introduction

A code C is called *self-dual* if $C = C^{\perp}$. A binary self-dual code C is called *doubly even* and *singly even* if all codewords have weight $\equiv 0 \pmod 4$ and if some codeword has weight $\equiv 2 \pmod 4$, respectively. It was shown in [7] that the minimum weight d of a doubly even self-dual code of length n is bounded by $d \leq 4[n/24] + 4$. We call a doubly even self-dual code meeting this upper bound *extremal*. The existence of an extremal doubly even self-dual code of length 72 is a long-standing open question (see [8, Section 12]).

Let D_p and D_b be codes with generator matrices of the form

$$\begin{pmatrix} I_n & R \end{pmatrix} \tag{1}$$

and

$$\begin{pmatrix} & 0 & 1 \cdots 1 \\ & 1 & \\ I_{n+1} & \vdots & R' \\ & 1 & \end{pmatrix}, \qquad (2)$$

respectively, where I_n is the identity matrix of order n and R and R' are $n \times n$ circulant matrices. The codes D_p and D_b are called *pure double circulant* and *bordered double circulant*, respectively. The two families are called double circulant codes.

All extremal double circulant doubly even self-dual codes of lengths up to 72 are known (cf. [6]). In this note, we give a classification of all double circulant doubly even self-dual $[72, 36, 12]$ codes in order to demonstrate that every double circulant doubly even self-dual $[72, 36, 12]$ code has no extremal doubly even self-dual $[72, 36, 16]$ neighbor.

2 Double circulant doubly even self-dual [72, 36, 12] codes

The possible weight enumerators for doubly even self-dual codes are determined by the Gleason theorem. For example, the possible weight enumerators for doubly even self-dual $[72, 36, 12]$ codes are as follows [4]:

$$1 + (4398 + \alpha)y^{12} + (197073 - 12\alpha)y^{16} + (18396972 + 66\alpha)y^{20} + \cdots$$

where α is an integer. Some doubly even self-dual $[72, 36, 12]$ codes are known (e.g. [3], [4], [5]). In this section, we give a classification of double circulant doubly even self-dual $[72, 36, 12]$ codes. Our approach is similar to that given in [6], so we omit the details.

All 5316 distinct pure double circulant doubly even self-dual $[72, 36, 12]$ codes have been found by exhaustive search. Then using MAGMA we determined the equivalence classes among these codes. We complete the classification of pure double circulant doubly even self-dual $[72, 36, 12]$ codes P_i by listing in Table 5 the first rows r of R in generator matrices (1). Here the rows are written in hexadecimal using $0 = (0000)$, $1 = (0001), \ldots,\ 9 = (1001), a = (1010), \ldots, f = (1111)$.

Similarly, we complete the classification of bordered double circulant doubly even self-dual $[72, 36, 12]$ codes B_i by listing in Table 6 the first rows r of R' in generator matrices (2). Here the rows are written in hexadecimal and obtained by omitting the first zero in each row.

Table 1: Automorphism groups for P_i and B_i

Codes	P_i ($i \neq 443$)	B_i ($i \neq 2, 6, 134$)	B_2	B_6	P_{443}, B_{134}
$\lvert\mathrm{Aut}\rvert$	72	70	210	840	178920

The orders $|\,\mathrm{Aut}\,|$ of the automorphism groups of P_i and B_i are given in Table 1. We remark that P_{443}, B_{134} are equivalent to the extended quadratic residue code QR_{72}. By comparing their automorphism groups, there is no pair of equivalent pure and bordered codes except the pair (P_{443}, B_{134}).

Hence we have the following:

Proposition 1. *There are* 443 *inequivalent pure double circulant doubly even self-dual* $[72, 36, 12]$ *codes. There are* 134 *inequivalent bordered double circulant doubly even self-dual* $[72, 36, 12]$ *codes. There are* 576 *inequivalent double circulant doubly even self-dual* $[72, 36, 12]$ *codes.*

The integers α in the weight enumerators of P_i and B_i are given in Tables 2 and 3, respectively.

3 Their Neighbors

First we give some observations from [1] on self-dual codes constructed by neighbors. Let C be a self-dual $[n, n/2, d]$ code. Let M be a matrix whose rows are the codewords of weight d in C. Suppose that there exists a vector $x \in \mathbb{F}_2^n$ such that

$$M\,{}^t x = {}^t\boldsymbol{j}, \tag{3}$$

where $\boldsymbol{j}$ is the all-one vector and ${}^t v$ denotes the transpose of a vector v. Set $C_0 = \langle x\rangle^\perp \cap C$. Then C_0 is a subcode of index 2 in C. If the weight of x is even then we have the two self-dual neighbors $\langle C_0, x\rangle$ and $\langle C_0, x + y\rangle$ of C for some $y \in C \setminus C_0$, which do not have any codeword of weight d in C. When C has a self-dual $[n, n/2, d']$ neighbor C' with $d' \geq d+2$, (3) has a solution x and we can obtain C' in this way. If $\mathrm{rank}\, M < \mathrm{rank}(M, {}^t\boldsymbol{j})$ then C has no self-dual $[n, n/2, d']$ neighbor C' with $d' \geq d+2$.

In Table 4, the ranks $(\mathrm{rank}\, M, \mathrm{rank}(M, {}^t\boldsymbol{j}))$ are listed for P_i and B_i, where r_1 and r_2 denote $\mathrm{rank}\, M$ and $\mathrm{rank}(M, {}^t\boldsymbol{j})$, respectively. For every double circulant doubly even self-dual $[72, 36, 12]$ code, $\mathrm{rank}\, M < \mathrm{rank}(M, {}^t\boldsymbol{j})$. Hence we have the following:

Proposition 2. *Every double circulant doubly even self-dual* $[72, 36, 12]$ *code has no extremal doubly even self-dual* $[72, 36, 16]$ *neighbor.*

In this case, it is sufficient to consider only $\mathrm{rank}\, M$ and $\mathrm{rank}(M, {}^t\boldsymbol{j})$ to show that there is no extremal doubly even self-dual $[72, 36, 16]$ neighbor.

Remark 3. Every double circulant doubly even self-dual $[72, 36, 12]$ code has no singly even self-dual $[72, 36, 14]$ neighbor.

Table 2: Weight enumerators for P_i

i	α	i	α	i	α	i	α
1	−4008	2	−3978	3	−3972	4	−3936
5, 6	−3924	7	−3894	8	−3870	9	−3846
10, 11	−3840	12	−3834	13	−3828	14	−3816
15	−3810	16	−3798	17	−3786	18, 19, 20	−3768
21, 22	−3756	23	−3750	24, 25, 26	−3744	27, 28, 29	−3732
30, 31	−3726	32	−3720	33	−3714	34	−3708
35, 36, 37	−3696	38	−3684	39	−3678	40, 41, 42	−3672
43, 44	−3666	45, 46, 47	−3660	48	−3648	49	−3642
50, 51	−3636	$52, \dots, 57$	−3630	$58, \dots, 61$	−3624	$62, \dots, 67$	−3612
68	−3606	$69, \dots, 73$	−3600	74	−3594	75	−3588
76	−3582	$77, \dots, 84$	−3576	85, 86, 87	−3570	$88, \dots, 92$	−3564
$93, \dots, 96$	−3558	97, 98	−3552	99, 100	−3546	$101, \dots, 107$	−3540
108	−3534	109	−3528	$110, \dots, 113$	−3522	114, 115, 116	−3516
$117, \dots, 122$	−3510	$123, \dots, 127$	−3504	128, 129, 130	−3498	$131, \dots, 134$	−3492
135, 136, 137	−3486	138, 139	−3474	$140, \dots, 146$	−3468	147, 148, 149	−3462
150, 151, 152	−3456	153, 154, 155	−3450	$156, \dots, 160$	−3444	161, 162	−3438
$163, \dots, 167$	−3432	$168, \dots, 172$	−3426	173, 174, 175	−3420	176, 177, 178	−3414
179	−3408	$180, \dots, 184$	−3402	185	−3384	$186, \dots, 189$	−3378
$190, \dots, 193$	−3372	194, 195, 196	−3366	$197, \dots, 202$	−3360	$203, \dots, 206$	−3354
207, 208, 209	−3348	$210, \dots, 213$	−3342	214, 215, 216	−3336	217, 218	−3330
219	−3324	$220, \dots, 224$	−3318	$225, \dots, 228$	−3312	$229, \dots, 236$	−3306
237, 238, 239	−3300	240, 241	−3294	$242, \dots, 249$	−3288	$250, \dots, 253$	−3282
$254, \dots, 257$	−3276	$258, \dots, 264$	−3270	265	−3264	266	−3258
$267, \dots, 272$	−3252	273	−3246	274, 275	−3240	$276, \dots, 279$	−3234
280, 281	−3228	282, 283	−3222	284, 285, 286	−3216	287, 288	−3210
289, 290	−3204	$291, \dots, 296$	−3198	297, 298, 299	−3192	$300, \dots, 303$	−3186
$304, \dots, 315$	−3180	316	−3174	317, 318	−3168	$319, \dots, 325$	−3162
326, 327, 328	−3144	329	−3138	$330, \dots, 333$	−3126	334	−3120
335, 336	−3114	337, 338, 339	−3108	340, 341, 342	−3102	$343, \dots, 349$	−3090
350, 351	−3084	352	−3078	$353, \dots, 356$	−3072	357, 358, 359	−3054
360, 361, 362	−3042	$363, \dots, 366$	−3036	$367, \dots, 372$	−3018	373, 374	−3012
$375, \dots, 378$	−3006	379, 380	−3000	381, 382	−2994	$383, \dots, 386$	−2982
387	−2976	388	−2970	$389, \dots, 393$	−2958	394	−2952
$395, \dots, 398$	−2946	399, 400	−2934	401	−2928	402, 403	−2922
404	−2916	405	−2910	406, 407, 408	−2904	409, 410	−2898
411	−2892	412	−2886	413	−2880	414	−2874
415	−2856	416, 417	−2838	418	−2826	419, 420	−2820
421	−2814	422	−2772	423	−2742	424, 425	−2730
426	−2724	427	−2718	428, 429	−2694	430	−2676
431	−2670	432	−2652	433	−2646	434, 435	−2640
436	−2616	437	−2592	438	−2586	439	−2568
440	−2502	441	−2394	442	−2340	443	−1416

Table 3: Weight enumerators for B_i

i	α	i	α	i	α
$1,\dots,7$	-3936	$8,\dots,20$	-3726	$21,\dots,57$	-3516
$58,\dots,97$	-3306	$98,\dots,116$	-3096	$117,\dots,129$	-2886
$130,131$	-2676	$132,133$	-2466	134	-1416

Table 4: Ranks for P_i and B_i

(r_1,r_2)	Codes
$(35,36)$	P_{22}, P_{24}, P_{54}, P_{66}, P_{86}, P_{93}, P_{125}, P_{126}, P_{135}, P_{136}, P_{153}, P_{176}, P_{177}, P_{193}, P_{236}, P_{244}, P_{273}, P_{309}, P_{338}, P_{339}, P_{397}, B_{42}, B_{124}, B_{130}
$(36,37)$	the other codes

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(Received 12 Jan 2007)

Table 5: Pure double circulant doubly even self-dual $[72, 36, 12]$ codes P_i

i	r	i	r	i	r	i	r	i	r
1	020deb307	2	002647dcb	3	017e3997b	4	004775ddf	5	00c7b6bcf
6	02ff4358f	7	037630bef	8	0ade7e7f3	9	072339f97	10	010ffb735
11	014cfdf93	12	0215bdd77	13	029a9b67f	14	037074efb	15	001165cfd
16	012c94ccf	17	00439c5b7	18	013177cef	19	0533b9d67	20	09b8d7ffd
21	015eb3b73	22	01b19be77	23	0014f7c4b	24	006698aeb	25	00f5bc2ef
26	02fbd6077	27	0080d5f9b	28	0225f3839	29	02ef58ecb	30	00436c2bf
31	073dde9bf	32	0044d9abb	33	0018df653	34	012df0feb	35	00129bc5f
36	028acc7ff	37	06ea927e7	38	008dae0f3	39	021d67cfb	40	006bfb5c7
41	01c5c9bef	42	01deabeff	43	0137dad67	44	035d2c7b7	45	002ecf613
46	0047eeddd	47	024eb6f2f	48	028ede76b	49	017cafdc3	50	00a4bc3ab
51	028bf7b4d	52	002ce671b	53	0032cec67	54	01215eea3	55	017e7e4d3
56	02a733bd7	57	04afe4cdd	58	0027b8937	59	004eeb307	60	018f2507b
61	0449dfc77	62	0046d9c73	63	00bfc79ab	64	013f3987f	65	041df571f
66	05979b83f	67	07868ef2f	68	0156afd6b	69	002aa86df	70	00aec7e5f
71	0238cbff5	72	0324f9cef	73	05b5bd7ef	74	04dd93bb9	75	008d6cac7
76	006e3abfb	77	000b4d1f7	78	0028fe783	79	009e9a875	80	014b8365b
81	01cef0dd7	82	0266778fb	83	02ba1b6fd	84	099f3baff	85	0030d9e57
86	0565cee8f	87	073e126bf	88	0134d6aff	89	0269ede97	90	02abcdb75
91	04bec6e1f	92	0e6f3bbcf	93	00330acf7	94	00675b9f7	95	0090c973f
96	023a8fdf9	97	024d6e5f7	98	037fb8457	99	002f3aaff	100	04dc347f7
101	003308fe7	102	00a5a6c37	103	0223779ef	104	031ffc8ab	105	0649d4fd7
106	08dfdf5f9	107	095ff76bb	108	08ff67263	109	00ab16acb	110	0033ebc07
111	0168d8ffd	112	0233cdc13	113	07ae18b3f	114	0505d8fbf	115	068747cf7
116	06ef614d7	117	009d218ef	118	00caf3e6f	119	014dcff93	120	022bf787b
121	045e345ff	122	0561eedcd	123	008d2ce1f	124	00ccb6527	125	017efb193
126	01b179e9f	127	025ab9cfb	128	0024cfb8b	129	004af1597	130	010d655ab
131	0015746db	132	00c9fb74f	133	031a9adf7	134	05ef17fdb	135	0169e620f
136	017c337db	137	017cf274f	138	004af878d	139	05277fe0d	140	008c04f7f
141	010aeb617	142	0165edb9d	143	020d2eaf1	144	025f9e9d5	145	02e77cacb
146	06cde68d7	147	004e313dd	148	030ba767f	149	04964b7bf	150	00e3ed4bf
151	0134c5e35	152	0586b7ecb	153	01375bcb7	154	015bb9dcb	155	036ceefef
156	0061eac67	157	0086959db	158	02bfae0e7	159	0425ebd77	160	09d5baeff
161	0016ae1f3	162	008dba875	163	0005ebb27	164	005181e7f	165	008761ba7
166	04c7e60ff	167	074efd9ef	168	0125fe8f7	169	0137299ff	170	01b3f1d2f
171	0431f2def	172	04a2d9f7b	173	01ba5ced7	174	01e7ed0af	175	0272fe957
176	008711bf5	177	00953aacd	178	035fb235b	179	026e36fad	180	033ff5f8f
181	04637fb1d	182	053f3bebf	183	0a3f3fddd	184	0ddfdee27	185	02bd8ed37
186	00455d32f	187	013de635f	188	0146e7195	189	1229fefef	190	0028d5d3b
191	017077deb	192	01b532df7	193	05dbf1d83	194	01c5a7d9f	195	02864774b
196	05ffdcea7	197	0005f9f13	198	000a1c5a3	199	00361aad7	200	0049f464f
201	009eb80d7	202	01b3f3c1f	203	009de76f9	204	0117afc6f	205	017b9ce67
206	026d5db8f	207	0016585f7	208	04c2ff397	209	06dbd229f	210	004fdd305
211	0137a52c3	212	016afd727	213	0b14dfff7	214	0093e6837	215	013e1d0cb
216	021dc7323	217	009dbd757	218	045ccebd7	219	070fb89af	220	0022dbe87
221	005d650eb	222	02bac7767	223	032df319f	224	032e136ff	225	0156ae79f
226	02cbd32df	227	04ea7f335	228	0aebf9fc7	229	0068627db	230	00b3e5e77
231	020466fb9	232	0229eeafb	233	026f5b1d7	234	0291baf5f	235	02b9a5cfb
236	02e826ff7	237	0086eb599	238	09c6ffdbb	239	0d91bbfef	240	016355dfb
241	025fb8dd5	242	0006da3af	243	002a5cf2b	244	0059b174b	245	005d6b6f7
246	011173e95	247	013e1dd7d	248	033c9d577	249	064afddff	250	0125f39bf

Table 5: Pure double circulant doubly even self-dual $[72, 36, 12]$ codes P_i (continued)

i	r	i	r	i	r	i	r	i	r
251	013bb87f5	252	02c99cf9f	253	071ba663f	254	005156add	255	00d2fe3d7
256	01db4ea77	257	02ad179bf	258	00249285d	259	0036913e7	260	0037ba847
261	01454ecc7	262	01510bdd3	263	02fafaca3	264	047d6378f	265	014a3167b
266	08b73f7fd	267	00011ae65	268	002a4cd7d	269	043d7579d	270	04aac69ff
271	04ab97dab	272	05be979ff	273	013dafcc7	274	017cf0eaf	275	0a9beefd7
276	0012e1f1f	277	00414962b	278	01c549eff	279	042764eff	280	002f559a3
281	019e9dfff	282	00486bf33	283	01026c7bb	284	0199f3cb7	285	022beeeb9
286	0468fd577	287	009fef16b	288	048bfb65b	289	013798faf	290	06bd1df7f
291	002a8e9b7	292	00c22675f	293	0127d19a5	294	02ff59aa3	295	0533bbc57
296	0d3cd7f3f	297	00c3d3633	298	03570cfe7	299	037ce315f	300	00096be37
301	04a21337d	302	058b1d57f	303	0cdefe737	304	000110cef	305	000b6e63b
306	0091fc693	307	010e9725b	308	0154399d3	309	0174b3bdb	310	019855f7f
311	0269e350b	312	03414ffb7	313	056fd434f	314	06cbdf67f	315	0b79fe72f
316	049efb60f	317	0213ecdf7	318	052699feb	319	008eef119	320	00916be8d
321	0141f8c75	322	099559e3f	323	09a7fcaff	324	09b7adeef	325	0b55dfef3
326	0155ebe67	327	0320ebebf	328	04cff19d3	329	014efe95b	330	00bae1dbf
331	015f636af	332	032cc6fcf	333	09f6adfeb	334	08c3e8eef	335	04df157b3
336	0556af4f3	337	000bcce9b	338	01085f7b1	339	0411c5e3b	340	01a85efe7
341	02560fdfb	342	02e8b2587	343	0001348ed	344	0032da973	345	00bbf2053
346	00bd5ebb3	347	017aa677d	348	01bee19af	349	0259ccf9f	350	004381fdb
351	004949bbb	352	034969ddf	353	010849ebf	354	013b73e3d	355	05fab3713
356	06e2fdf5f	357	039eddddf	358	03b657ff7	359	0527dbd27	360	00299617f
361	046aebe2f	362	04daf2e2f	363	004626fb9	364	00529cd67	365	0135b3adf
366	026c7babb	367	0025d46ed	368	008c92afd	369	013d8d8c3	370	01446e74d
371	0175d2f2f	372	0278faeab	373	04d1d4edf	374	072fd8717	375	0296ebab7
376	0897bf77f	377	0a1f57fbf	378	0e7e36d7f	379	06e9267b7	380	09de3bbfb
381	01c378e7f	382	043f8f9e3	383	005c0f5d3	384	0085b335d	385	02171f8c9
386	05bc5ffb7	387	04ebf66a3	388	008e95d33	389	010ffe85f	390	0267ddba5
391	0297ef94b	392	0628c7bdf	393	07470e9bf	394	02db4bc7b	395	00693338f
396	0093d5c2b	397	0128f261f	398	098fcf939	399	02353ddf5	400	0add3afdf
401	05fb7d6bb	402	00f3d8e3f	403	02fc187ef	404	0275f99ab	405	00cefa74f
406	00884cff5	407	013a55df7	408	0987ffcbf	409	009a4eec5	410	04af31beb
411	011191e7d	412	013e8ede7	413	0183b6edf	414	00614aeb7	415	00bb2d7eb
416	015a267ff	417	02b13afdd	418	026af34ef	419	0040c4f7f	420	00cc2cf1b
421	0105f03cf	422	029a4bd7f	423	06ba87d4f	424	00257ccc7	425	0208d8bcf
426	05d5d4acf	427	011ccfed7	428	01bfe6157	429	01d5068d7	430	004347de9
431	01e8a37df	432	000c6b7b3	433	0575dcc8f	434	00227e7a9	435	019b79e37
436	032d7bfbf	437	00b3ec777	438	089bff623	439	0000bce43	440	00abebcbd
441	0089163fd	442	023df4e79	443	02ddc36dd				

Table 6: Bordered double circulant doubly even self-dual $[72, 36, 12]$ codes B_i

i	r	i	r	i	r	i	r	i	r
1	001d75d9f	2	00bc1216f	3	010cea58b	4	014e57bb3	5	0165ef51d
6	04ef8e935	7	059f74fe7	8	000188717	9	00038b1ef	10	00093141d
11	000b2e56b	12	0014c1d77	13	002f3510f	14	005d35beb	15	00ccfc9b7
16	0173bebbf	17	019eb21df	18	02562dde7	19	02bdedbeb	20	05399f77f
21	00089dee5	22	0008e7da9	23	0014cf3a3	24	00166d64b	25	00396eee7
26	004d5fc77	27	004fd3b9b	28	00539a5ff	29	006eb3d8f	30	006f5dc2f
31	008e994a7	32	0092af77b	33	0095b53f7	34	00976bb9b	35	00a14af63
36	00b635f57	37	00bf8b8b7	38	0106a7dbf	39	01292bfdb	40	012fb5997
41	01439edf3	42	015f92f4b	43	017295e9f	44	017bcf6fd	45	018bd48ff
46	018ded8f3	47	019d1755f	48	019ef518f	49	01a35d9eb	50	01aff6097
51	0277dfe5d	52	0366fd3df	53	0479bef77	54	047f4ff6b	55	04afbdc7f
56	0537f76f5	57	06effe7bf	58	0004ed8f5	59	00085eaf9	60	000d4b95b
61	001589e2f	62	001852d3f	63	0027332c7	64	00320a5ef	65	004268cdf
66	0042fd8d1	67	0047797af	68	004a713e3	69	004bff34b	70	004f8aaff
71	005feda1b	72	0066630b7	73	00912759d	74	009bc97e7	75	009bd1bf3
76	009f6ab9d	77	00ad579cf	78	00b0c56b3	79	00bf26f27	80	00e4b778f
81	010755d91	82	0122efdab	83	01261efb7	84	0127468e5	85	013f539c7
86	013fdae0b	87	015a8f69f	88	017ba6ff7	89	01879eacf	90	02147df97
91	030f0c7f7	92	03973efb7	93	03be0efbf	94	056afff87	95	06eb3d76f
96	0767effef	97	077b1cebf	98	00004d5c5	99	0005d6747	100	0009a5bad
101	0012ea597	102	001695b47	103	001d5e6ef	104	0027da7d7	105	0047ec835
106	004977bf9	107	004fff057	108	005ef714f	109	00ad73d2f	110	0162ae7af
111	016b2e5cf	112	0185996ff	113	01a9b547f	114	02b71ef7f	115	03d7cd9df
116	078d3b7df	117	00004399d	118	001995c8f	119	0028956e7	120	0032fb737
121	004f47b7d	122	005f293bf	123	006a5c547	124	0094d1fbf	125	0117dad79
126	02cf2a69f	127	046d6fff9	128	046fdefe5	129	095b3edef	130	00559b057
131	015b64f9d	132	00231fb7f	133	012b8dabf	134	0013f684b		