

## REPRESENTATIONS BY QUATERNARY QUADRATIC FORMS WITH COEFFICIENTS 1, 2, 5 OR 10

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ABSTRACT. We determine explicit formulas for the number of representations of a positive integer  $n$  by quaternary quadratic forms with coefficients 1, 2, 5 or 10. We use a modular forms approach.

### 1. Introduction

Let  $\mathbb{N}$ ,  $\mathbb{N}_0$ ,  $\mathbb{Z}$  and  $\mathbb{C}$  denote the sets of positive integers, nonnegative integers, integers and complex numbers, respectively. For  $n \in \mathbb{N}$  we set  $\sigma(n) = \sum_{d|n} d$ , where  $d$  runs through the positive divisors of  $n$ . If  $n \notin \mathbb{N}$  we set  $\sigma(n) = 0$ . For  $a_1, a_2, a_3, a_4 \in \mathbb{N}$ , and  $n \in \mathbb{N}_0$  we define

$$N(a_1, a_2, a_3, a_4; n) := \text{card}\{(x_1, x_2, x_3, x_4) \in \mathbb{Z}^4 \mid n = a_1x_1^2 + a_2x_2^2 + a_3x_3^2 + a_4x_4^2\}.$$

It is a classical result of Jacobi [7, 21] that

$$N(1, 1, 1, 1; n) = 8\sigma(n) - 32\sigma(n/4).$$

Formulas for  $N(a_1, a_2, a_3, a_4; n)$  for the quaternary quadratic forms

$(a_1, a_2, a_3, a_4) = (1, 1, 1, 2), (1, 1, 2, 2), (1, 2, 2, 2), (1, 1, 1, 5), (1, 1, 5, 5), (1, 5, 5, 5)$

are in the literature, see for example [1–3, 9, 12–17, 20].

There are twenty-six quaternary quadratic forms  $a_1x_1^2 + a_2x_2^2 + a_3x_3^2 + a_4x_4^2$ , where  $a_1, a_2, a_3, a_4 \in \{1, 2, 5, 10\}$ ,  $a_1 \leq a_2 \leq a_3 \leq a_4$  and  $\gcd(a_1, a_2, a_3, a_4) = 1$  (see Table 2.1). In this paper, we determine an explicit formula for  $N(a_1, a_2, a_3, a_4; n)$  for each of these quaternary forms in a uniform manner. We use a modular forms approach.

For  $q \in \mathbb{C}$  with  $|q| < 1$ , Ramanujan's theta function  $\varphi(q)$  is defined by

$$\varphi(q) = \sum_{n=-\infty}^{\infty} q^{n^2}.$$

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For  $a_1, a_2, a_3, a_4 \in \mathbb{N}$  we have

$$(1.1) \quad \sum_{n=1}^{\infty} N(a_1, a_2, a_3, a_4; n) q^n = \varphi(q^{a_1}) \varphi(q^{a_2}) \varphi(q^{a_3}) \varphi(q^{a_4}).$$

The Dedekind eta function  $\eta(z)$  is the holomorphic function defined on the upper half plane  $\mathbb{H} = \{z \in \mathbb{C} \mid \text{Im}(z) > 0\}$  by

$$\eta(z) = e^{\pi iz/12} \prod_{n=1}^{\infty} (1 - e^{2\pi inz}).$$

Throughout the remainder of the paper we take  $q = q(z) := e^{2\pi iz}$  with  $z \in \mathbb{H}$ . Thus we can express  $\eta(z)$  as

$$(1.2) \quad \eta(z) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n).$$

An eta quotient is defined to be a finite product of the form

$$f(z) = \prod_{\delta} \eta^{r_{\delta}}(\delta z),$$

where  $\delta$  runs through a finite set of positive integers and the exponents  $r_{\delta}$  are non-zero integers. It is known (see for example [5, Corollary 1.3.4]) that

$$(1.3) \quad \varphi(q) = \frac{\eta^5(2z)}{\eta^2(z)\eta^2(4z)}.$$

## 2. Modular spaces $M_2(\Gamma_0(40), \chi_i)$ with $i \in \{0, 1, 2, 3\}$

For  $n \in \mathbb{N}$  and Dirichlet characters  $\chi$  and  $\psi$  we define  $\sigma_{\chi, \psi}(n)$  by

$$(2.1) \quad \sigma_{\chi, \psi}(n) := \sum_{1 \leq m|n} \psi(m) \chi(n/m) m.$$

If  $n \notin \mathbb{N}$  we set  $\sigma_{\chi, \psi}(n) = 0$ . Let  $\chi_0$  denote the trivial character, that is  $\chi_0(n) = 1$  for all  $n \in \mathbb{Z}$ . Hence  $\sigma_{\chi_0, \chi_0}(n)$  coincides with the sum of divisors function  $\sigma(n)$ . Let  $N \in \mathbb{N}$ . The modular subgroup  $\Gamma_0(N)$  is defined by

$$\Gamma_0(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{Z}, ad - bc = 1, c \equiv 0 \pmod{N} \right\}.$$

Let  $\chi$  be a Dirichlet character of modulus dividing  $N$  and let  $k \in \mathbb{Z}$ . We write  $M_k(\Gamma_0(N), \chi)$  to denote the space of modular forms of weight  $k$  with multiplier system  $\chi$  for  $\Gamma_0(N)$ , and  $E_k(\Gamma_0(N), \chi)$  and  $S_k(\Gamma_0(N), \chi)$  to denote the subspaces of Eisenstein forms and cusp forms of  $M_k(\Gamma_0(N), \chi)$ , respectively. If  $\chi = \chi_0$ , then we write  $M_k(\Gamma_0(N))$  for  $M_k(\Gamma_0(N), \chi_0)$ , and  $S_k(\Gamma_0(N))$  for  $S_k(\Gamma_0(N), \chi_0)$ . It is known (see for example [19, p. 83]) that

$$(2.2) \quad M_k(\Gamma_0(N), \chi) = E_k(\Gamma_0(N), \chi) \oplus S_k(\Gamma_0(N), \chi).$$

For  $n \in \mathbb{Z}$  we define three Dirichlet characters by

$$(2.3) \quad \chi_1(n) = \left(\frac{5}{n}\right), \quad \chi_2(n) = \left(\frac{8}{n}\right), \quad \chi_3(n) = \left(\frac{40}{n}\right).$$

We define the Eisenstein series

$$(2.4) \quad L(q) := E_{\chi_0, \chi_0}(q) = -\frac{1}{24} + \sum_{n=1}^{\infty} \sigma(n)q^n,$$

$$(2.5) \quad E_{\chi_0, \chi_1}(q) = -\frac{1}{5} + \sum_{n=1}^{\infty} \sigma_{\chi_0, \chi_1}(n)q^n, \quad E_{\chi_1, \chi_0}(q) = \sum_{n=1}^{\infty} \sigma_{\chi_1, \chi_0}(n)q^n,$$

$$(2.6) \quad E_{\chi_0, \chi_2}(q) = -\frac{1}{2} + \sum_{n=1}^{\infty} \sigma_{\chi_0, \chi_2}(n)q^n, \quad E_{\chi_2, \chi_0}(q) = \sum_{n=1}^{\infty} \sigma_{\chi_2, \chi_0}(n)q^n,$$

$$(2.7) \quad E_{\chi_0, \chi_3}(q) = -7 + \sum_{n=1}^{\infty} \sigma_{\chi_0, \chi_3}(n)q^n, \quad E_{\chi_3, \chi_0}(q) = \sum_{n=1}^{\infty} \sigma_{\chi_3, \chi_0}(n)q^n,$$

$$(2.8) \quad E_{\chi_1, \chi_2}(q) = \sum_{n=1}^{\infty} \sigma_{\chi_1, \chi_2}(n)q^n, \quad E_{\chi_2, \chi_1}(q) = \sum_{n=1}^{\infty} \sigma_{\chi_2, \chi_1}(n)q^n.$$

We use the following lemma to determine if certain eta quotients are modular forms. See [6, p. 174], [10, Corollary 2.3, p. 37], [8, Theorem 5.7, p. 101], [11] and [18, Theorem 1.64].

**Lemma 2.1** (Ligozat). *Let  $N \in \mathbb{N}$  and  $f(z) = \prod_{1 \leq \delta | N} \eta^{r_\delta}(\delta z)$  be an eta quotient. Let  $s = \prod_{1 \leq \delta | N} \delta^{|r_\delta|}$  and  $k = \frac{1}{2} \sum_{1 \leq \delta | N} r_\delta$ . Suppose that the following conditions are satisfied:*

- (L1)  $\sum_{1 \leq \delta | N} \delta \cdot r_\delta \equiv 0 \pmod{24}$ ,
- (L2)  $\sum_{1 \leq \delta | N} \frac{N}{\delta} \cdot r_\delta \equiv 0 \pmod{24}$ ,
- (L3)  $\sum_{1 \leq \delta | N} \frac{\gcd(d, \delta)^2 \cdot r_\delta}{\delta} \geq 0$  for each positive divisor  $d$  of  $N$ ,
- (L4)  $k$  is an integer.

Then  $f(z) \in M_k(\Gamma_0(N), \chi)$ , where the character  $\chi$  is given by  $\chi(m) = \left(\frac{(-1)^k s}{m}\right)$ .

(L3)' *In addition to the above conditions, if the inequality in (L3) is strict for each positive divisor  $d$  of  $N$ , then  $f(z) \in S_k(\Gamma_0(N), \chi)$ .*

In Table 2.1, we group our twenty-six quaternary forms  $(a_1, a_2, a_3, a_4)$  according to modular spaces  $M_2(\Gamma_0(40), \chi)$  to which  $\varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4})$  belong.

Formulas  $N(a_1, a_2, a_3, a_4; n)$  for the forms with a checkmark ( $\checkmark$ ) in Table 2.1 are known. Of the remaining nineteen forms, four are universal and identified with an asterisk (\*).

We deduce from [19, Sec. 6.1, p. 93] that

$$(2.9) \quad \dim(E_2(\Gamma_0(40))) = 7, \quad \dim(S_2(\Gamma_0(40))) = 3.$$

Table 2.1

$M_2(\Gamma_0(40))$	$M_2(\Gamma_0(40), \chi_1)$	$M_2(\Gamma_0(40), \chi_2)$	$M_2(\Gamma_0(40), \chi_3)$
(1, 1, 1, 1)✓	(1, 1, 1, 5)✓	(1, 1, 1, 2)✓	(1, 1, 1, 10)
(1, 1, 2, 2)✓	(1, 1, 2, 10)*	(1, 1, 5, 10)	(1, 1, 2, 5)*
(1, 1, 5, 5)✓	(1, 2, 2, 5)*	(1, 2, 2, 2)✓	(1, 2, 2, 10)
(1, 1, 10, 10)	(1, 5, 5, 5)✓	(1, 2, 5, 5)	(1, 5, 5, 10)
(1, 2, 5, 10)*	(1, 5, 10, 10)	(1, 2, 10, 10)	(1, 10, 10, 10)
(2, 2, 5, 5)	(2, 5, 5, 10)	(2, 2, 5, 10)	(2, 2, 2, 5)
			(2, 5, 5, 5)
			(2, 5, 10, 10)

We also deduce from [19, Sec. 6.3, p. 98] that

$$(2.10) \quad \dim(E_2(\Gamma_0(40), \chi_1)) = 8, \quad \dim(S_2(\Gamma_0(40), \chi_1)) = 2,$$

$$(2.11) \quad \dim(E_2(\Gamma_0(40), \chi_2)) = 4, \quad \dim(S_2(\Gamma_0(40), \chi_2)) = 4,$$

$$(2.12) \quad \dim(E_2(\Gamma_0(40), \chi_3)) = 4, \quad \dim(S_2(\Gamma_0(40), \chi_3)) = 4.$$

**Theorem 2.1.** *Let  $\chi_1, \chi_2, \chi_3$  be as in (2.3). If  $(a_1, a_2, a_3, a_4)$  is in the first, second, third or fourth column of Table 2.1, then*

$$\begin{aligned} \varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) &\in M_2(\Gamma_0(40)), \\ \varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) &\in M_2(\Gamma_0(40), \chi_1), \\ \varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) &\in M_2(\Gamma_0(40), \chi_2), \\ \varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) &\in M_2(\Gamma_0(40), \chi_3), \end{aligned}$$

respectively.

*Proof.* The assertion directly follows from (1.3) and Lemma 2.1.  $\square$

Let  $n \in \mathbb{N}$ . We define the eta quotients  $A_k(q)$ ,  $B_k(q)$ ,  $C_k(q)$ ,  $D_k(q)$  and integers  $a_k(n)$ ,  $b_k(n)$ ,  $c_k(n)$ ,  $d_k(n)$  as follows:

$$(2.13) \quad A_1(q) = \sum_{n=1}^{\infty} a_1(n)q^n = \eta^2(2z)\eta^2(10z),$$

$$(2.14) \quad A_2(q) = A_1(q^2) = \sum_{n=1}^{\infty} a_2(n)q^n = \eta^2(4z)\eta^2(20z),$$

$$(2.15) \quad A_3(q) = \sum_{n=1}^{\infty} a_3(n)q^n = \frac{\eta^5(4z)\eta(10z)\eta^2(40z)}{\eta(2z)\eta^2(8z)\eta(20z)},$$

$$(2.16) \quad B_1(q) = \sum_{n=1}^{\infty} b_1(n)q^n = \frac{\eta(2z)\eta^4(20z)}{\eta(10z)},$$

$$(2.17) \quad B_2(q) = \sum_{n=1}^{\infty} b_2(n)q^n = \frac{\eta^4(4z)\eta(10z)}{\eta(2z)},$$

$$(2.18) \quad C_1(q) = \sum_{n=1}^{\infty} c_1(n)q^n = \frac{\eta^2(z)\eta(8z)\eta^2(10z)\eta(40z)}{\eta(2z)\eta(20z)},$$

$$(2.19) \quad C_2(q) = \sum_{n=1}^{\infty} c_2(n)q^n = \frac{\eta(z)\eta(5z)\eta^2(8z)\eta^2(20z)}{\eta(4z)\eta(10z)},$$

$$(2.20) \quad C_3(q) = \sum_{n=1}^{\infty} c_3(n)q^n = \frac{\eta^6(2z)\eta(10z)\eta^2(40z)}{\eta^2(z)\eta^2(4z)\eta(20z)},$$

$$(2.21) \quad C_4(q) = \sum_{n=1}^{\infty} c_4(n)q^n = \frac{\eta^6(4z)\eta^2(5z)\eta(20z)}{\eta^2(2z)\eta^2(8z)\eta(10z)},$$

$$(2.22) \quad D_1(q) = \sum_{n=1}^{\infty} d_1(n)q^n = \frac{\eta^2(z)\eta^6(4z)\eta(20z)}{\eta^3(2z)\eta^2(8z)},$$

$$(2.23) \quad D_2(q) = \sum_{n=1}^{\infty} d_2(n)q^n = \frac{\eta^2(5z)\eta(8z)\eta(10z)\eta(40z)}{\eta(20z)},$$

$$(2.24) \quad D_3(q) = \sum_{n=1}^{\infty} d_3(n)q^n = \frac{\eta(z)\eta(5z)\eta(20z)\eta^2(40z)}{\eta(10z)},$$

$$(2.25) \quad D_4(q) = \sum_{n=1}^{\infty} d_4(n)q^n = \frac{\eta(z)\eta(4z)\eta(5z)\eta^2(8z)}{\eta(2z)}.$$

**Theorem 2.2.** *Let  $\chi_1, \chi_2, \chi_3$  be as in (2.3). Then*

$$\{A_1(q), A_2(q), A_3(q)\}, \quad \{B_1(q), B_2(q)\}, \\ \{C_1(q), C_2(q), C_3(q), C_4(q)\}, \quad \{D_1(q), D_2(q), D_3(q), D_4(q)\}$$

are bases for  $S_2(\Gamma_0(40))$ ,  $S_2(\Gamma_0(40), \chi_1)$ ,  $S_2(\Gamma_0(40), \chi_2)$  and  $S_2(\Gamma_0(40), \chi_3)$ , respectively.

*Proof.* The set  $\{A_1(q), A_2(q), A_3(q)\}$  is linearly independent over  $\mathbb{C}$ . By Lemma 2.1, we have  $A_k(q) \in S_2(\Gamma_0(40))$  for  $k = 1, 2, 3$ . The assertion now follows from (2.9). Similarly, the remaining three assertions follow from (2.10), (2.11), (2.12) and Lemma 2.1.  $\square$

**Theorem 2.3.** *Let  $\chi_0$  be the trivial character and  $\chi_1, \chi_2, \chi_3$  be as in (2.3). Then*

$$\{L(q) - tL(q^t) \mid t = 2, 4, 5, 8, 10, 20, 40\}, \\ \{E_{\chi_0, \chi_1}(q^t), E_{\chi_1, \chi_0}(q^t) \mid t = 1, 2, 4, 8\}, \\ \{E_{\chi_0, \chi_2}(q^t), E_{\chi_2, \chi_0}(q^t) \mid t = 1, 5\}, \\ \{E_{\chi_0, \chi_3}(q), E_{\chi_1, \chi_2}(q), E_{\chi_2, \chi_1}(q), E_{\chi_3, \chi_0}(q)\}$$

are bases for  $E_2(\Gamma_0(40))$ ,  $E_2(\Gamma_0(40), \chi_1)$ ,  $E_2(\Gamma_0(40), \chi_2)$  and  $E_2(\Gamma_0(40), \chi_3)$ , respectively.

*Proof.* The assertions follow from [19, Theorem 5.9] with  $\chi = \psi = \chi_0$ ;  $\epsilon = \chi_1$  and  $\chi, \psi \in \{\chi_0, \chi_1\}$ ;  $\epsilon = \chi_2$  and  $\chi, \psi \in \{\chi_0, \chi_2\}$ ;  $\epsilon = \chi_3$  and  $\chi, \psi \in \{\chi_0, \chi_1, \chi_2, \chi_3\}$ , respectively.  $\square$

**Theorem 2.4.** *Let  $\chi_0$  be the trivial character and  $\chi_1, \chi_2, \chi_3$  be as in (2.3). Then*

$$\begin{aligned} & \{L(q) - tL(q^t) \mid t = 2, 4, 5, 8, 10, 20, 40\} \cup \{A_1(q), A_2(q), A_3(q)\}, \\ & \{E_{\chi_0, \chi_1}(q^t), E_{\chi_1, \chi_0}(q^t) \mid t = 1, 2, 4, 8\} \cup \{B_1(q), B_2(q)\}, \\ & \{E_{\chi_0, \chi_2}(q^t), E_{\chi_2, \chi_0}(q^t) \mid t = 1, 5\} \cup \{C_k(q) \mid k = 1, 2, 3, 4\}, \\ & \{E_{\chi_0, \chi_3}(q), E_{\chi_1, \chi_2}(q), E_{\chi_2, \chi_1}(q), E_{\chi_3, \chi_0}(q)\} \cup \{D_k(q) \mid k = 1, 2, 3, 4\} \end{aligned}$$

are bases for  $M_2(\Gamma_0(40))$ ,  $M_2(\Gamma_0(40), \chi_1)$ ,  $M_2(\Gamma_0(40), \chi_2)$ ,  $M_2(\Gamma_0(40), \chi_3)$ , respectively.

*Proof.* The assertions follow from (2.2), Theorems 2.2 and 2.3.  $\square$

We now give four theorems (Theorems 2.5–2.8) from which the theorems of Section 3 (Theorems 3.1–3.4) follow.

**Theorem 2.5.** *We have*

$$\begin{aligned} \varphi^4(q) &= 8L(q) - 32L(q^4), \\ \varphi^2(q)\varphi^2(q^2) &= 4L(q) - 4L(q^2) + 8L(q^4) - 32L(q^8), \\ \varphi^2(q)\varphi^2(q^5) &= \frac{4}{3}L(q) - \frac{16}{3}L(q^4) + \frac{20}{3}L(q^5) - \frac{80}{3}L(q^{20}) + \frac{8}{3}A_1(q), \\ \varphi^2(q)\varphi^2(q^{10}) &= \frac{2}{3}L(q) - \frac{2}{3}L(q^2) + \frac{4}{3}L(q^4) + \frac{10}{3}L(q^5) - \frac{16}{3}L(q^8) \\ &\quad - \frac{10}{3}L(q^{10}) + \frac{20}{3}L(q^{20}) - \frac{80}{3}L(q^{40}) + \frac{10}{3}A_1(q) \\ &\quad + \frac{8}{3}A_2(q) + 4A_3(q), \\ \varphi(q)\varphi(q^2)\varphi(q^5)\varphi(q^{10}) &= L(q) - L(q^2) - 2L(q^4) - 5L(q^5) + 8L(q^8) \\ &\quad + 5L(q^{10}) + 10L(q^{20}) - 40L(q^{40}) + A_1(q) + 2A_3(q), \\ \varphi^2(q^2)\varphi^2(q^5) &= \frac{2}{3}L(q) - \frac{2}{3}L(q^2) + \frac{4}{3}L(q^4) + \frac{10}{3}L(q^5) - \frac{16}{3}L(q^8) \\ &\quad - \frac{10}{3}L(q^{10}) + \frac{20}{3}L(q^{20}) - \frac{80}{3}L(q^{40}) - \frac{2}{3}A_1(q) \\ &\quad + \frac{8}{3}A_2(q) - 4A_3(q). \end{aligned}$$

*Proof.* Let  $(a_1, a_2, a_3, a_4)$  be any of the quaternary quadratic forms listed in the first column of Table 2.1. By Theorem 2.1 we have  $\varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) \in M_2(\Gamma_0(40))$ . By Theorem 2.4,  $\varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4})$  must be a linear combination of  $L(q) - tL(q^t)$  ( $t = 2, 4, 5, 8, 10, 20, 40$ ) and  $A_k(q)$  ( $k \in \{1, 2, 3\}$ ),

namely

$$\begin{aligned}
 & \varphi(q^{a_1})\varphi(q^{a_2})\varphi(q^{a_3})\varphi(q^{a_4}) \\
 &= x_1(L(q) - 2L(q^2)) + x_2(L(q) - 4L(q^4)) \\
 & \quad + x_3(L(q) - 5L(q^5)) + x_4(L(q) - 8L(q^8)) \\
 (2.26) \quad & \quad + x_5(L(q) - 10L(q^{10})) + x_6(L(q) - 20L(q^{20})) \\
 & \quad + x_7(L(q) - 40L(q^{40})) + y_1A_1(q) + y_2A_2(q) + y_3A_3(q).
 \end{aligned}$$

We only prove the last equation in the theorem as the others can be proven similarly. Let  $(a_1, a_2, a_3, a_4) = (2, 2, 5, 5)$ . Appealing to [8, Theorem 3.13], we find that the Sturm bound for the modular space  $M_2(\Gamma_0(40))$  is 12. So, equating the coefficients of  $q^n$  for  $0 \leq n \leq 12$  on both sides of (2.26), we find a system of linear equations with the unknowns  $x_i$  ( $1 \leq i \leq 7$ ),  $y_1$ ,  $y_2$  and  $y_3$ . Using MAPLE we solve the system and find that

$$x_1 = x_5 = \frac{1}{3}, \quad x_2 = x_6 = -\frac{1}{3}, \quad x_3 = y_1 = -\frac{2}{3}, \quad x_4 = x_7 = \frac{2}{3}, \quad y_2 = \frac{8}{3}, \quad y_3 = -4.$$

Substituting these values back in (2.26), and with the obvious simplifications, we find the asserted equation.  $\square$

**Corollary 2.1.** *Let  $n \in \mathbb{N}$ . We have*

$$N(1, 1, 10, 10; n) = N(2, 2, 5, 5; n) \text{ if } n \equiv 0 \pmod{2}.$$

*Proof.* From Theorem 2.5, we have

$$(2.27) \quad \varphi^2(q)\varphi^2(q^{10}) - \varphi^2(q^2)\varphi^2(q^5) = 4A_1(q) + 8A_3(q).$$

It is clear from (1.2), (2.13) and (2.15) that

$$(2.28) \quad a_1(n) = a_3(n) = 0 \text{ if } n \equiv 0 \pmod{2}.$$

The assertion now follows from (1.1), (2.27) and (2.28).  $\square$

Similarly to Theorem 2.5, Theorems 2.6–2.8 follow from Theorems 2.1 and 2.4.

**Theorem 2.6.** *Let  $\chi_0$  be the trivial character and  $\chi_1$  be as in (2.3). Then*

$$\begin{aligned}
 \varphi^3(q)\varphi(q^5) &= E_{\chi_0, \chi_1}(q) - 2E_{\chi_0, \chi_1}(q^2) - 4E_{\chi_0, \chi_1}(q^4) + 5E_{\chi_1, \chi_0}(q) \\
 & \quad + 10E_{\chi_1, \chi_0}(q^2) - 20E_{\chi_1, \chi_0}(q^4), \\
 \varphi^2(q)\varphi(q^2)\varphi(q^{10}) &= -\frac{1}{2}E_{\chi_0, \chi_1}(q) + \frac{1}{2}E_{\chi_0, \chi_1}(q^2) - E_{\chi_0, \chi_1}(q^4) \\
 & \quad - 4E_{\chi_0, \chi_1}(q^8) + \frac{5}{2}E_{\chi_1, \chi_0}(q) + \frac{5}{2}E_{\chi_1, \chi_0}(q^2) \\
 & \quad + 5E_{\chi_1, \chi_0}(q^4) - 20E_{\chi_1, \chi_0}(q^8) + 2B_2(q), \\
 \varphi(q)\varphi^2(q^2)\varphi(q^5) &= \frac{1}{2}E_{\chi_0, \chi_1}(q) - \frac{1}{2}E_{\chi_0, \chi_1}(q^2) - E_{\chi_0, \chi_1}(q^4)
 \end{aligned}$$

$$\begin{aligned}
& -4E_{\chi_0, \chi_1}(q^8) + \frac{5}{2}E_{\chi_1, \chi_0}(q) + \frac{5}{2}E_{\chi_1, \chi_0}(q^2) \\
& -5E_{\chi_1, \chi_0}(q^4) + 20E_{\chi_1, \chi_0}(q^8) + 5B_1(q) - B_2(q), \\
\varphi(q)\varphi^3(q^5) &= E_{\chi_0, \chi_1}(q) - 2E_{\chi_0, \chi_1}(q^2) - 4E_{\chi_0, \chi_1}(q^4) + E_{\chi_1, \chi_0}(q) \\
& + 2E_{\chi_1, \chi_0}(q^2) - 4E_{\chi_1, \chi_0}(q^4), \\
\varphi(q)\varphi(q^5)\varphi^2(q^{10}) &= \frac{1}{2}E_{\chi_0, \chi_1}(q) - \frac{1}{2}E_{\chi_0, \chi_1}(q^2) - E_{\chi_0, \chi_1}(q^4) \\
& - 4E_{\chi_0, \chi_1}(q^8) + \frac{1}{2}E_{\chi_1, \chi_0}(q) + \frac{1}{2}E_{\chi_1, \chi_0}(q^2) \\
& - E_{\chi_1, \chi_0}(q^4) + 4E_{\chi_1, \chi_0}(q^8) - B_1(q) + B_2(q), \\
\varphi(q^2)\varphi^2(q^5)\varphi(q^{10}) &= -\frac{1}{2}E_{\chi_0, \chi_1}(q) + \frac{1}{2}E_{\chi_0, \chi_1}(q^2) - E_{\chi_0, \chi_1}(q^4) \\
& - 4E_{\chi_0, \chi_1}(q^8) + \frac{1}{2}E_{\chi_1, \chi_0}(q) + \frac{1}{2}E_{\chi_1, \chi_0}(q^2) \\
& + E_{\chi_1, \chi_0}(q^4) - 4E_{\chi_1, \chi_0}(q^8) - 2B_1(q).
\end{aligned}$$

**Theorem 2.7.** *Let  $\chi_0$  be the trivial character and  $\chi_2$  be as in (2.3). Then*

$$\begin{aligned}
\varphi^3(q)\varphi(q^2) &= -2E_{\chi_0, \chi_2}(q) + 8E_{\chi_2, \chi_0}(q), \\
\varphi^2(q)\varphi(q^5)\varphi(q^{10}) &= \frac{2}{13}(2E_{\chi_0, \chi_2}(q) - 15E_{\chi_0, \chi_2}(q^5) + 8E_{\chi_2, \chi_0}(q) \\
& + 60E_{\chi_2, \chi_0}(q^5)) + \frac{8}{13}(6C_1(q) - 4C_2(q) - 3C_3(q) \\
& + 4C_4(q)), \\
\varphi(q)\varphi^3(q^2) &= -2E_{\chi_0, \chi_2}(q) + 4E_{\chi_2, \chi_0}(q), \\
\varphi(q)\varphi(q^2)\varphi^2(q^5) &= \frac{2}{13}(-3E_{\chi_0, \chi_2}(q) - 10E_{\chi_0, \chi_2}(q^5) + 12E_{\chi_2, \chi_0}(q)) \\
& - \frac{80}{13}E_{\chi_2, \chi_0}(q^5) + \frac{8}{13}(-2C_2(q) - 5C_3(q) + C_4(q)), \\
\varphi(q)\varphi(q^2)\varphi^2(q^{10}) &= \frac{2}{13}(-3E_{\chi_0, \chi_2}(q) - 10E_{\chi_0, \chi_2}(q^5) + 6E_{\chi_2, \chi_0}(q)) \\
& - \frac{40}{13}E_{\chi_2, \chi_0}(q^5) + \frac{4}{13}(2C_1(q) - 2C_3(q) + 5C_4(q)), \\
\varphi^2(q^2)\varphi(q^5)\varphi(q^{10}) &= \frac{2}{13}(2E_{\chi_0, \chi_2}(q) - 15E_{\chi_0, \chi_2}(q^5) + 4E_{\chi_2, \chi_0}(q) \\
& + 30E_{\chi_2, \chi_0}(q^5)) + \frac{4}{13}(-4C_1(q) + 12C_2(q) + 8C_3(q) \\
& - 3C_4(q)).
\end{aligned}$$

**Theorem 2.8.** *Let  $\chi_0$  be the trivial character and  $\chi_1, \chi_2, \chi_3$  be as in (2.3). Then*

$$\varphi^3(q)\varphi(q^{10}) = \frac{1}{7}(-E_{\chi_0, \chi_3}(q) - 5E_{\chi_1, \chi_2}(q) + 4E_{\chi_2, \chi_1}(q) + 20E_{\chi_3, \chi_0}(q))$$



$$\begin{aligned}
& + \frac{4}{7}(-3D_1(q) + 15D_2(q) - 15D_3(q) + 9D_4(q)), \\
\varphi^2(q)\varphi(q^2)\varphi(q^5) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) + 5E_{\chi_1, \chi_2}(q) - 4E_{\chi_2, \chi_1}(q) + 20E_{\chi_3, \chi_0}(q)) \\
& + \frac{8}{7}(-D_1(q) + 2D_4(q)), \\
\varphi(q)\varphi^2(q^2)\varphi(q^{10}) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) - 5E_{\chi_1, \chi_2}(q) + 2E_{\chi_2, \chi_1}(q) + 10E_{\chi_3, \chi_0}(q)) \\
& + \frac{4}{7}(D_1(q) + 5D_2(q) + 5D_3(q) + D_4(q)), \\
\varphi(q)\varphi^2(q^5)\varphi(q^{10}) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) - E_{\chi_1, \chi_2}(q) + 4E_{\chi_2, \chi_1}(q) + 4E_{\chi_3, \chi_0}(q)) \\
& + \frac{8}{7}(D_2(q) - D_3(q) + D_4(q)), \\
\varphi(q)\varphi^3(q^{10}) &= -\frac{1}{7}(E_{\chi_0, \chi_3}(q) + E_{\chi_1, \chi_2}(q) - 2E_{\chi_2, \chi_1}(q) - 2E_{\chi_3, \chi_0}(q)) \\
& + \frac{12}{7}(D_2(q) + D_3(q) + D_4(q)), \\
\varphi^3(q^2)\varphi(q^5) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) + 5E_{\chi_1, \chi_2}(q) - 2E_{\chi_2, \chi_1}(q) + 10E_{\chi_3, \chi_0}(q)) \\
& - 12D_1(q), \\
\varphi(q^2)\varphi^3(q^5) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) + E_{\chi_1, \chi_2}(q) - 4E_{\chi_2, \chi_1}(q) + 4E_{\chi_3, \chi_0}(q)) \\
& - \frac{12}{7}(D_1(q) + D_2(q) + 3D_3(q) - D_4(q)), \\
\varphi(q^2)\varphi(q^5)\varphi^2(q^{10}) &= \frac{1}{7}(-E_{\chi_0, \chi_3}(q) + E_{\chi_1, \chi_2}(q) - 2E_{\chi_2, \chi_1}(q) + 2E_{\chi_3, \chi_0}(q)) \\
& + \frac{4}{7}(-D_1(q) + D_2(q) - 3D_3(q) + D_4(q)).
\end{aligned}$$

### 3. Main results

**Theorem 3.1.** *Let  $n \in \mathbb{N}$ . We have*

$$\begin{aligned}
N(1, 1, 5, 5; n) &= \frac{4}{3}\sigma(n) - \frac{16}{3}\sigma(n/4) + \frac{20}{3}\sigma(n/5) - \frac{80}{3}\sigma(n/20) + \frac{8}{3}a_1(n), \\
N(1, 1, 10, 10; n) &= \frac{2}{3}\sigma(n) - \frac{2}{3}\sigma(n/2) + \frac{4}{3}\sigma(n/4) + \frac{10}{3}\sigma(n/5) - \frac{16}{3}\sigma(n/8) \\
& - \frac{10}{3}\sigma(n/10) + \frac{20}{3}\sigma(n/20) - \frac{80}{3}\sigma(n/40) + \frac{10}{3}a_1(n) \\
& + \frac{8}{3}a_2(n) + 4a_3(n), \\
N(1, 2, 5, 10; n) &= \sigma(n) - \sigma(n/2) - 2\sigma(n/4) - 5\sigma(n/5) + 8\sigma(n/8) \\
& + 5\sigma(n/10) + 10\sigma(n/20) - 40\sigma(n/40) + a_1(n) + 2a_3(n),
\end{aligned}$$

$$\begin{aligned}
N(2, 2, 5, 5; n) &= \frac{2}{3}\sigma(n) - \frac{2}{3}\sigma(n/2) + \frac{4}{3}\sigma(n/4) + \frac{10}{3}\sigma(n/5) - \frac{16}{3}\sigma(n/8) \\
&\quad - \frac{10}{3}\sigma(n/10) + \frac{20}{3}\sigma(n/20) - \frac{80}{3}\sigma(n/40) - \frac{2}{3}a_1(n) \\
&\quad + \frac{8}{3}a_2(n) - 4a_3(n).
\end{aligned}$$

*Proof.* The assertions follow from (1.1), (2.4) and Theorem 2.5.  $\square$

**Theorem 3.2.** *Let  $n \in \mathbb{N}$ . Let  $\sigma_{\chi_i, \chi_j}(n)$  be as in (2.1) for  $i, j \in \{0, 1\}$ . We have*

$$\begin{aligned}
N(1, 1, 1, 5; n) &= \sigma_{\chi_0, \chi_1}(n) - 2\sigma_{\chi_0, \chi_1}(n/2) - 4\sigma_{\chi_0, \chi_1}(n/4) \\
&\quad + 5\sigma_{\chi_1, \chi_0}(n) + 10\sigma_{\chi_1, \chi_0}(n/2) - 20\sigma_{\chi_1, \chi_0}(n/4), \\
N(1, 1, 2, 10; n) &= -\frac{1}{2}\sigma_{\chi_0, \chi_1}(n) + \frac{1}{2}\sigma_{\chi_0, \chi_1}(n/2) - \sigma_{\chi_0, \chi_1}(n/4) \\
&\quad - 4\sigma_{\chi_0, \chi_1}(n/8) + \frac{5}{2}\sigma_{\chi_1, \chi_0}(n) + \frac{5}{2}\sigma_{\chi_1, \chi_0}(n/2) \\
&\quad + 5\sigma_{\chi_1, \chi_0}(n/4) - 20\sigma_{\chi_1, \chi_0}(n/8) + 2b_2(n), \\
N(1, 2, 2, 5; n) &= \frac{1}{2}\sigma_{\chi_0, \chi_1}(n) - \frac{1}{2}\sigma_{\chi_0, \chi_1}(n/2) - \sigma_{\chi_0, \chi_1}(n/4) - 4\sigma_{\chi_0, \chi_1}(n/8) \\
&\quad + \frac{5}{2}\sigma_{\chi_1, \chi_0}(n) + \frac{5}{2}\sigma_{\chi_1, \chi_0}(n/2) - 5\sigma_{\chi_1, \chi_0}(n/4) \\
&\quad + 20\sigma_{\chi_1, \chi_0}(n/8) + 5b_1(n) - b_2(n), \\
N(1, 5, 5, 5; n) &= \sigma_{\chi_0, \chi_1}(n) - 2\sigma_{\chi_0, \chi_1}(n/2) - 4\sigma_{\chi_0, \chi_1}(n/4) \\
&\quad + \sigma_{\chi_1, \chi_0}(n) + 2\sigma_{\chi_1, \chi_0}(n/2) - 4\sigma_{\chi_1, \chi_0}(n/4), \\
N(1, 5, 10, 10; n) &= \frac{1}{2}\sigma_{\chi_0, \chi_1}(n) - \frac{1}{2}\sigma_{\chi_0, \chi_1}(n/2) - \sigma_{\chi_0, \chi_1}(n/4) - 4\sigma_{\chi_0, \chi_1}(n/8) \\
&\quad + \frac{1}{2}\sigma_{\chi_1, \chi_0}(n) + \frac{1}{2}\sigma_{\chi_1, \chi_0}(n/2) - \sigma_{\chi_1, \chi_0}(n/4) \\
&\quad + 4\sigma_{\chi_1, \chi_0}(n/8) - b_1(n) + b_2(n), \\
N(2, 5, 5, 10; n) &= -\frac{1}{2}\sigma_{\chi_0, \chi_1}(n) + \frac{1}{2}\sigma_{\chi_0, \chi_1}(n/2) - \sigma_{\chi_0, \chi_1}(n/4) \\
&\quad - 4\sigma_{\chi_0, \chi_1}(n/8) + \frac{1}{2}\sigma_{\chi_1, \chi_0}(n) + \frac{1}{2}\sigma_{\chi_1, \chi_0}(n/2) \\
&\quad + \sigma_{\chi_1, \chi_0}(n/4) - 4\sigma_{\chi_1, \chi_0}(n/8) - 2b_1(n).
\end{aligned}$$

*Proof.* The assertions follow from (1.1), (2.5) and Theorem 2.6.  $\square$

**Theorem 3.3.** *Let  $n \in \mathbb{N}$ . Let  $\sigma_{\chi_i, \chi_j}(n)$  be as in (2.1) for  $i, j \in \{0, 2\}$ . Then*

$$\begin{aligned}
N(1, 1, 1, 2; n) &= -2\sigma_{\chi_0, \chi_2}(n) + 8\sigma_{\chi_2, \chi_0}(n), \\
N(1, 1, 5, 10; n) &= \frac{2}{13}(2\sigma_{\chi_0, \chi_2}(n) - 15\sigma_{\chi_0, \chi_2}(n/5) + 8\sigma_{\chi_2, \chi_0}(n))
\end{aligned}$$

$$\begin{aligned}
& + 60\sigma_{\chi_2, \chi_0}(n/5) + \frac{8}{13}(6c_1(n) - 4c_2(n) - 3c_3(n) \\
& + 4c_4(n)), \\
N(1, 2, 2, 2; n) &= -2\sigma_{\chi_0, \chi_2}(n) + 4\sigma_{\chi_2, \chi_0}(n), \\
N(1, 2, 5, 5; n) &= -\frac{2}{13}(3\sigma_{\chi_0, \chi_2}(n) + 10\sigma_{\chi_0, \chi_2}(n/5) - 12\sigma_{\chi_2, \chi_0}(n) \\
& + 40\sigma_{\chi_2, \chi_0}(n/5)) + \frac{8}{13}(-2c_2(n) - 5c_3(n) + c_4(n)), \\
N(1, 2, 10, 10; n) &= \frac{2}{13}(-3\sigma_{\chi_0, \chi_2}(n) - 10\sigma_{\chi_0, \chi_2}(n/5) + 6\sigma_{\chi_2, \chi_0}(n) \\
& - 20\sigma_{\chi_2, \chi_0}(n/5)) + \frac{4}{13}(2c_1(n) - 2c_3(n) + 5c_4(n)), \\
N(2, 2, 5, 10; n) &= \frac{2}{13}(2\sigma_{\chi_0, \chi_2}(n) - 15\sigma_{\chi_0, \chi_2}(n/5) + 4\sigma_{\chi_2, \chi_0}(n) \\
& + 30\sigma_{\chi_2, \chi_0}(n/5)) + \frac{4}{13}(-4c_1(n) + 12c_2(n) + 8c_3(n) \\
& - 3c_4(n)).
\end{aligned}$$

*Proof.* The assertions follow from (1.1), (2.6) and Theorem 2.7.  $\square$

**Theorem 3.4.** *Let  $n \in \mathbb{N}$ . Let  $\sigma_{\chi_i, \chi_j}(n)$  be as in (2.1) for  $i, j \in \{0, 1, 2, 3\}$ . Then*

$$\begin{aligned}
N(1, 1, 1, 10; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) - 5\sigma_{\chi_1, \chi_2}(n) + 4\sigma_{\chi_2, \chi_1}(n) + 20\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{4}{7}(-3d_1(n) + 15d_2(n) - 15d_3(n) + 9d_4(n)), \\
N(1, 1, 2, 5; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) + 5\sigma_{\chi_1, \chi_2}(n) - 4\sigma_{\chi_2, \chi_1}(n) + 20\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{8}{7}(-d_1(n) + 2d_4(n)), \\
N(1, 2, 2, 10; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) - 5\sigma_{\chi_1, \chi_2}(n) + 2\sigma_{\chi_2, \chi_1}(n) + 10\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{4}{7}(d_1(n) + 5d_2(n) + 5d_3(n) + d_4(n)), \\
N(1, 5, 5, 10; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) - \sigma_{\chi_1, \chi_2}(n) + 4\sigma_{\chi_2, \chi_1}(n) + 4\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{8}{7}(d_2(n) - d_3(n) + d_4(n)), \\
N(1, 10, 10, 10; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) - \sigma_{\chi_1, \chi_2}(n) + 2\sigma_{\chi_2, \chi_1}(n) + 2\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{12}{7}(d_2(n) + d_3(n) + d_4(n)), \\
N(2, 2, 2, 5; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) + 5\sigma_{\chi_1, \chi_2}(n) - 2\sigma_{\chi_2, \chi_1}(n) + 10\sigma_{\chi_3, \chi_0}(n))
\end{aligned}$$

$$\begin{aligned}
& -\frac{12}{7}d_1(n), \\
N(2, 5, 5, 5; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) + \sigma_{\chi_1, \chi_2}(n) - 4\sigma_{\chi_2, \chi_1}(n) + 4\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{12}{7}(-d_1(n) - d_2(n) - 3d_3(n) + d_4(n)), \\
N(2, 5, 10, 10; n) &= \frac{1}{7}(-\sigma_{\chi_0, \chi_3}(n) + \sigma_{\chi_1, \chi_2}(n) - 2\sigma_{\chi_2, \chi_1}(n) + 2\sigma_{\chi_3, \chi_0}(n)) \\
& + \frac{4}{7}(-d_1(n) + d_2(n) - 3d_3(n) + d_4(n)).
\end{aligned}$$

*Proof.* The assertions follow from (1.1), (2.7), (2.8) and Theorem 2.8.  $\square$

#### 4. Remarks

*Remark 4.1.* Replacing  $q$  by  $-q$  in  $\varphi^3(q)\varphi(q^5)$  in Theorem 2.6, we have

$$\begin{aligned}
\varphi^3(-q)\varphi(-q^5) &= E_{\chi_0, \chi_1}(-q) - 2E_{\chi_0, \chi_1}(q^2) - 4E_{\chi_0, \chi_1}(q^4) \\
(4.1) \quad & + 5E_{\chi_1, \chi_0}(-q) + 10E_{\chi_1, \chi_0}(q^2) - 20E_{\chi_1, \chi_0}(q^4).
\end{aligned}$$

Appealing to Theorem 2.3, we obtain

$$(4.2) \quad E_{\chi_0, \chi_1}(-q) = -E_{\chi_0, \chi_1}(q) - 2E_{\chi_0, \chi_1}(q^2) + 4E_{\chi_0, \chi_1}(q^4),$$

$$(4.3) \quad E_{\chi_1, \chi_0}(-q) = -E_{\chi_1, \chi_0}(q) + 2E_{\chi_1, \chi_0}(q^2) + 4E_{\chi_1, \chi_0}(q^4).$$

Substituting (4.2) and (4.3) in (4.1), we obtain

$$(4.4) \quad \varphi^3(-q)\varphi(-q^5) = -E_{\chi_0, \chi_1}(q) - 4E_{\chi_0, \chi_1}(q^2) - 5E_{\chi_1, \chi_0}(q) + 20E_{\chi_1, \chi_0}(q^2).$$

It can easily be seen that

$$(4.5) \quad -E_{\chi_0, \chi_1}(q) - 4E_{\chi_0, \chi_1}(q^2) = 1 + \sum_{n=1}^{\infty} \left( \sum_{d|n} (-1)^d \binom{5}{d} d \right) q^n,$$

$$(4.6) \quad -E_{\chi_1, \chi_0}(q) + 4E_{\chi_1, \chi_0}(q^2) = \sum_{n=1}^{\infty} \left( \sum_{d|n} (-1)^d \binom{5}{n/d} d \right) q^n.$$

Now, appealing to (1.1) and (4.4)–(4.6), we obtain

$$\begin{aligned}
& \sum_{n=0}^{\infty} N(1, 1, 1, 5; n)(-q)^n \\
&= \varphi^3(-q)\varphi(-q^5) \\
&= 1 + \sum_{n=1}^{\infty} \left( \sum_{d|n} (-1)^d \binom{5}{d} d \right) q^n + 5 \sum_{n=1}^{\infty} \left( \sum_{d|n} (-1)^d \binom{5}{n/d} d \right) q^n,
\end{aligned}$$

from which we deduce

$$N(1, 1, 1, 5; n) = \sum_{d|n} (-1)^{n+d} \binom{5}{d} d + 5 \sum_{d|n} (-1)^{n+d} \binom{5}{n/d} d,$$

which agrees with known results, see for example [3, Theorem 5.1]. Similarly, one can show that our formula for  $N(1, 5, 5, 5; n)$  given in Theorem 3.2 agrees with the result in [3, Theorem 6.1].

*Remark 4.2.* Appealing to Lemma 2.1 and Theorem 2.3, we obtain the following identities:

$$\begin{aligned}
 L(q) - 4L(q^4) &= \frac{1}{8} \frac{\eta^{20}(2z)}{\eta^8(z)\eta^8(4z)}, \\
 E_{\chi_0, \chi_1}(q) &= -\frac{1}{5} \frac{\eta^5(z)}{\eta(5z)}, \\
 E_{\chi_1, \chi_0}(q) &= \frac{\eta^5(5z)}{\eta(z)}, \\
 E_{\chi_0, \chi_2}(q) &= -\frac{1}{2} \frac{\eta^2(z)\eta(2z)\eta^3(4z)}{\eta^2(8z)}, \\
 E_{\chi_2, \chi_0}(q) &= \frac{\eta^3(2z)\eta(4z)\eta^2(8z)}{\eta^2(z)}, \\
 E_{\chi_0, \chi_1}(q) + 4E_{\chi_0, \chi_1}(q^2) &= -\frac{\eta(z)\eta^2(2z)\eta^3(5z)}{\eta^2(10z)}, \\
 E_{\chi_1, \chi_0}(q) + E_{\chi_1, \chi_0}(q^2) &= \frac{\eta^3(2z)\eta^2(5z)\eta(10z)}{\eta^2(z)}, \\
 E_{\chi_1, \chi_0}(q) - 4E_{\chi_1, \chi_0}(q^2) &= \frac{\eta^3(z)\eta(5z)\eta^2(10z)}{\eta^2(2z)}, \\
 E_{\chi_0, \chi_2}(q) - 2E_{\chi_2, \chi_0}(q) &= -\frac{1}{2} \frac{\eta^{13}(4z)}{\eta^2(z)\eta(2z)\eta^6(8z)}, \\
 E_{\chi_0, \chi_2}(q) - 4E_{\chi_2, \chi_0}(q) &= -\frac{1}{2} \frac{\eta^{13}(2z)}{\eta^6(z)\eta(4z)\eta^2(8z)}, \\
 E_{\chi_0, \chi_1}(q) - 2E_{\chi_0, \chi_1}(q^2) - 4E_{\chi_0, \chi_1}(q^4) &= \frac{\eta^5(2z)\eta^7(10z)}{\eta(z)\eta(4z)\eta^3(5z)\eta^3(20z)}, \\
 E_{\chi_1, \chi_0}(q) + 2E_{\chi_1, \chi_0}(q^2) - 4E_{\chi_1, \chi_0}(q^4) &= \frac{\eta^7(2z)\eta^5(10z)}{\eta^3(z)\eta^3(4z)\eta(5z)\eta(20z)}.
 \end{aligned}$$

*Remark 4.3.* Set  $a := \varphi(q)$ ,  $b := \varphi(q^2)$ ,  $c := \varphi(q^5)$  and  $d := \varphi(q^{10})$ . We obtain the following identities from Theorem 2.8:

$$\begin{aligned}
 ad(-a^2 - b^2 + 5c^2 - 5d^2) + bc(5a^2 - 8b^2 - 5c^2 + 10d^2) &= 12D_1(q), \\
 ad(2a^2 - b^2 - 4c^2 + d^2) + bc(-a^2 + b^2 - 5c^2 + 7d^2) &= 24D_2(q), \\
 ad(-a^2 + 2b^2 - 7c^2 + 10d^2) + bc(-a^2 + 4b^2 + c^2 - 8d^2) &= 48D_3(q), \\
 ad(a^2 - 8b^2 - 5c^2 + 20d^2) + bc(7a^2 - 10b^2 + 5c^2 - 10d^2) &= 48D_4(q).
 \end{aligned}$$

*Remark 4.4.* It would be interesting to determine general formulas for the number of representations of a positive integer  $n$  by the quaternary quadratic

forms with coefficients in  $\{1, p, q, pq\}$ , where  $p$  and  $q$  are distinct prime numbers. The case when  $p = 2$  and  $q = 7$  is treated in [4].

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