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CENTRAL EXTENSIONS AND RATIONAL QUADRATIC FORMS

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Introduction

The purpose of this paper is to characterize by means of simple quadratic forms the set of rational primes that are decomposed completely in a non-abelian central extension which is abelian over a quadratic field. More precisely, let $L = \mathbf{Q}(\sqrt{d_1}, \sqrt{d_2})$ be a bicyclic biquadratic field, and let $K = \mathbf{Q}(\sqrt{d_1 d_2})$. Denote by $S_K(\tilde{m})$ the ray class field $\mathrm{mod}\, m$ of K in narrow sense for a large rational integer m. Let L_m^* be the maximal abelian extension over $\mathbf{Q}$ contained in $S_K(\tilde{m})$ and $\hat{L}_m$ be the maximal extension contained in $S_K(\tilde{m})$ such that $\mathrm{Gal}(\hat{L}_m/L)$ is contained in the center of $\mathrm{Gal}(\hat{L}_m/\mathbf{Q})$. Then we shall show in Theorem 2.1 that any rational prime p not dividing $d_1 d_2 m$ is decomposed completely in $L_m^*/\mathbf{Q}$ if and only if p is representable by rational integers x and y such that $x \equiv 1$ and $y \equiv 0 \,\mathrm{mod}\, m$ as follows

$$p = \frac{ax^2 + bxy + cy^2}{a},$$

where a, b, c are rational integers such that $b^2 - 4ac$ is equal to the discriminant of K and (a) is a norm of a representative of the ray class group of $K \,\mathrm{mod}\, m$. Moreover p is decomposed completely in $\hat{L}_m/L_m^*$ if and only if $\left(\frac{d_1}{a}\right) = 1$.

§1. Central extensions with respect to quadratic fields

Let d_1 and d_2 be square free integers and let $d_1 d_2 = d_0 d^2$, where d_0 is square free and $d_0 \neq 1$. Let $K = \mathbf{Q}(\sqrt{d_0})$, $L = \mathbf{Q}(\sqrt{d_1}, \sqrt{d_2})$ and D be the discriminant of K. For a rational integer m, denote by $\mathfrak{S}_K(\tilde{m})$ the ray class $\mathrm{mod}\, m$ of K in narrow sense, and by $S_K(\tilde{m})$ the ray class field $\mathrm{mod}\, m$ of K in narrow sense.

Let m be a rational integer such that L is contained in $S_K(\tilde{m})$. Let L_m^* and $\hat{L}_m$

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be the genus field and the central class field of $L/\mathbf{Q}$ with respect to $S_K(\tilde{m})$. They are by definition, the maximal subfields of $S_K(\tilde{m})$ such that L_m^* is abelian over $\mathbf{Q}$ and $\mathrm{Gal}(\hat{L}_m/L)$ is contained in the center of $\mathrm{Gal}(\hat{L}_m/\mathbf{Q})$.

We have $[\hat{L}_m : L_m^*] \leq 2$ in general, and $[\hat{L}_m : L_m^*] = 2$ when m is large enough, for instance m is a multiple of $4dd_0$. More precisely, let m_1 be the product of all odd rational primes q such that q divides d_0 and satisfies both $(d_1/q) \neq 1$ and $(d_2/q) \neq 1$. Define m_0 by

$$(1.1)\quad m_0 = \begin{cases} dm_1 & \text{when } d_1 \equiv d_2 \equiv 1 \mod 4, \\ dm_1 & \text{when } d_i \equiv 1 \mod 8, \text{ and } d_j \not\equiv 1 \mod 4, \\ 2dm_1 & \text{when } d_i \equiv 5 \mod 8, \text{ and } d_j \not\equiv 1 \mod 4, \\ 4dm_1 & \text{otherwise,} \end{cases}$$

where $i, j = 1$ or 2 and $i \neq j$. Then [2, Proposition 3.4] implies $[\hat{L}_m : L_m^*] = 2$ when m is a multiple of m_0.

Now let $K_\#^*$ be the genus field of K in absolute sense, and let $\mathbf{Q}(\tilde{m})$ be the ray class field $\bmod m$ of $\mathbf{Q}$ in narrow sense. Let K_m^* be the genus field of $K/\mathbf{Q}$ with respect to the ray class field $\bmod m$ of K in narrow sense. Then $K_m^* = L_m^*$ by the definition, and we have

$$L_m^* = K_\#^* \mathbf{Q}(\tilde{m})$$

by [2, Theorem 4.3]. Thus the genus field L_m^* is given explicitly as follows

$$(1.2)\qquad L_m^* = \Pi \mathbf{Q}(\sqrt{q^*}) \cdot \mathbf{Q}(\zeta_m)$$

where q runs over all rational primes dividing d_0, and q^* are prime discriminants, i.e., $D = \Pi q^*$ by $q^* = (-1)^{(q-1)/2} q$, -4, or ± 8.

For the later use, let $\mathfrak{S}'_K(m)$ be the group of principal ideals (α) of K such that $\alpha \equiv 1 \bmod m$ and $\mathbf{N}_{K/\mathbf{Q}}\alpha > 0$, and $S'_K(m)$ be the class field of K corresponding to $\mathfrak{S}'_K(m)$. Let $L_m^{*\prime}$ and $\hat{L}'_m$ be the genus field and the central class field of $L/\mathbf{Q}$ with respect to $S'_K(m)$. Then we can show that

$$(1.3)\qquad L_m^{*\prime} = L_m^*,$$

and

$$(1.4)\qquad \hat{L}'_m = \hat{L}_m$$

as follows.

The ideal group of K corresponding to $\mathbf{Q}(\tilde{m})$ is the group of ideals $\mathfrak{a}$ of K such that $|\mathbf{N}\mathfrak{a}| \equiv 1 \bmod m$. This group contains $\mathfrak{S}'_K(m)$ and clearly $S'_K(m) \supset K_\#^*$. Hence $S'_K(m)$ contains $L_m^* = K_\#^* \mathbf{Q}(\tilde{m})$. This implies (1.3) since $S_K(\tilde{m})$ contains

$S'_K(m)$.

In order to show (1.4), let σ be the non-trivial element of $\mathrm{Gal}(K/\mathbf{Q})$, and denote by $\mathfrak{K}$ resp. $\mathfrak{K}'$ the group of ideals $\mathfrak{a}$ of K such that $\mathfrak{a}^{\sigma} \equiv \mathfrak{a} \bmod \mathfrak{S}_K(\tilde{m})$ resp. $\bmod\, \mathfrak{S}'_K(m)$. Then by [1, Proposition 5.1] we have

$$\mathrm{Gal}(\hat{L}_m/L_m^*) \cong I_K/\mathfrak{H}(L/K)\mathfrak{K} \tag{1.5}$$

and

$$\mathrm{Gal}(\hat{L}'_m/L_m^{*\prime}) \cong I_K/\mathfrak{H}(L/K)\mathfrak{K}', \tag{1.6}$$

where I_K is the group of ideals of K prime to m and $\mathfrak{H}(L/K)$ is the subgroup of I_K corresponding to L by class field theory. Let $\alpha = 1 + 4\sqrt{D}m$. Then $(\alpha) \in \mathfrak{H}(L/K)$, because

$$\left(\frac{d_i}{N_{K/\mathbf{Q}}\alpha}\right) = \left(\frac{N_{K/\mathbf{Q}}\alpha}{d_i}\right) = 1$$

for $i = 1,2$, since $N_{K/\mathbf{Q}}\alpha \equiv 1 \bmod 8$. When $\mathfrak{S}'_K(m) \neq \mathfrak{S}_K(\tilde{m})$, the non-trivial class of $\mathfrak{S}'_K(m)/\mathfrak{S}_K(\tilde{m})$ is represented by $1 - m$, and $1 - m = \alpha^{1-\sigma}\alpha_1$, where $\alpha_1 = \alpha^{\sigma-1}(1 - m)$, which is contained in $\mathfrak{S}_K(\tilde{m})$. Thus for any element (γ) of $\mathfrak{S}'_K(m)$, we have $(\gamma) = (\alpha)^{1-\sigma}(\gamma_1)$, where $(\gamma_1) \in \mathfrak{S}_K(\tilde{m})$. Now let $\mathfrak{a}$ be any element of $\mathfrak{K}'$. Then there is γ of $K^{\times}$ such that $\mathfrak{a}^{\sigma} = \mathfrak{a}(\gamma)$, $(\gamma) \in \mathfrak{S}'_K(m)$. The above argument implies $(\mathfrak{a}(\alpha))^{\sigma} = \mathfrak{a}(\alpha)(\gamma_1)$, that is $\mathfrak{a}(\alpha) \in \mathfrak{K}$. Hence $\mathfrak{a} \in (\alpha)^{-1}\mathfrak{K} \subset \mathfrak{H}(L/K)\mathfrak{K}$. Therefore $[\hat{L}'_m : L_m^*] = 2$ if and only if $[\hat{L}_m : L_m^*] = 2$ by (1.3), (1.5) and (1.6). This implies further (1.4) because of definition of central extensions and $\mathfrak{S}_K(\tilde{m}) \subset \mathfrak{S}'_K(m)$.

§2. Decomposition of primes

Notation being as in the preceding section, let $\mathfrak{B}$ be an ideal of $L_m^* = L_m^{*\prime}$ prime to m. Then it follows from the definition of the genus field that there exists an ideal $\mathfrak{a}$ of K such that

$$\mathfrak{a}^{\sigma-1} \equiv \mathbf{N}_{L_m^*/K}\mathfrak{B} \mod \mathfrak{S}'_K(m). \tag{2.1}$$

Let $\mathfrak{b} = N_{L_m^*/K}\mathfrak{B}$ and $(a) = N_{K/\mathbf{Q}}\mathfrak{a}$. Suppose that no prime divisor of $\mathfrak{a}$ ramified in L. Then by [2, Proposition 1.5] exchanged the notation a and b, we have the following relation of Artin symbols:

$$\left(\frac{\hat{L}_m/L_m^*}{\mathfrak{B}}\right) = \left(\frac{\hat{L}_m/K}{\mathfrak{b}}\right) = \left(\frac{L/K}{\mathfrak{a}}\right) = \left(\frac{d_1}{a}\right) = \left(\frac{d_2}{a}\right). \tag{2.2}$$

Let $C'_m(\mathfrak{a})$ be the class of ideals of $K \bmod \mathfrak{S}'_K(m)$ which contains $\mathfrak{a}$, and let $\mathfrak{N}(C'_m(\mathfrak{a}))$ be the set of norms of "integral" ideals contained in $C'_m(\mathfrak{a})$. Then any rational prime of $\mathfrak{N}(C'_m(\mathfrak{a}^{1-\sigma}))$ not dividing m is decomposed completely in $L^*_m = L^{*\prime}_m$. It is further decomposed completely in $\hat{L}_m$ when $\left(\frac{d_1}{a}\right) = 1$ by (2.2), where $(a) = N_{K/\mathbf{Q}}\mathfrak{a}$.

Let us call a rational integer D a discriminant integer when there is a quadratic field whose discriminant is equal to D. For a discriminant integer D and a rational integer m, denote by $A(D, m)$ the set of rational integers a satisfying the following condition:

$$\begin{cases} a \text{ is square free, and g.c.d.}(a, m) = 1. \\ \left(\dfrac{D}{q}\right) = 1 \quad \text{for all odd prime factors } q \text{ of } a. \\ a \text{ is odd, if } D \not\equiv 1 \bmod 8. \end{cases} \tag{2.3}$$

Note that $a \in A(D, m)$ implies that (a) is a norm of an integral ideal of K prime to m.

For a rational integer a in $A(D, m)$, choose a primitive integral form $ax^2 + bxy + cy^2$ with discriminant D, and define $H(D, m, a)$ by

$$H(D, m, a) = \left\{\frac{ax^2 + bxy + cy^2}{a} \in \mathbf{Z}\,;\, x \equiv 1,\ y \equiv 0 \bmod m\right\}. \tag{2.4}$$

Note that $H(D, m, a)$ is independent of the choice of b, c, because if $b_1^2 - 4ac_1 = D$ too, then $b = b_1 + 2at$ by $t \in \mathbf{Z}$ and we have

$${}^tU \begin{bmatrix} a_1 & b_1/2 \\ b_1/2 & c_1 \end{bmatrix} U = \begin{bmatrix} a & b/2 \\ b/2 & c \end{bmatrix}$$

by $U = \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix}$.

THEOREM 2.1. *Let $L = \mathbf{Q}(\sqrt{d_1}, \sqrt{d_2})$, where d_1 and d_2 are distinct square free integers and $d_1 d_2 = d_0 d^2$ by a square free integer d_0. Let m be an integer divisible by m_0 defined in* (1.1). *Let L^*_m and $\hat{L}_m$ be the genus field and the central class field of $L/\mathbf{Q}$ with respect to the ray class field* mod *m of K. Let p be a rational prime not dividing $d_1 d_2 m$. Then p is decomposed completely in $L^*_m/\mathbf{Q}$ if and only if p is contained in $H(D, m, a)$ for some rational integer a of $A(D, m)$. It is further decomposed completely in $\hat{L}_m/L^*_m$ if and only if $\left(\frac{d_1}{a}\right) = 1$.*

Proof. By (2.2) and (2.1), it is enough to show that

$$p \in H(D, m, a) \Leftrightarrow p \in \mathfrak{N}(C'_m(\mathfrak{a}^{1-\sigma})), \tag{2.5}$$

where $\mathfrak{a}$ is an integral ideal of K and $(a) = \mathbf{N}_{K/\mathbf{Q}}\mathfrak{a}$.

Suppose that $p \in \mathfrak{N}(C'_m(\mathfrak{a}^{1-\sigma}))$. Then there are a prime ideal $\mathfrak{p}$ dividing p and an element α of K such that $\mathfrak{p} = (\alpha)\mathfrak{a}^{1-\sigma}$, $\alpha \equiv 1 \bmod m$ and $\alpha\alpha^\sigma > 0$. We can assume that $\mathfrak{a}$ contains no rational divisor. Then we have $\mathfrak{a}^{-1} \cap \mathbf{Q} = \mathbf{Z}$, since any multiple divisor of $\mathfrak{a}^{-1}$ is rational only if it is integral. Hence we can choose a $\mathbf{Z}$-basis of $\mathfrak{a}^{-1}$ in the form $\{1, \omega\}$ by an element ω of K. Let $\alpha = x + \omega y$, where $x, y \in \mathbf{Z}$. Then

$$p = \alpha\alpha^\sigma = (x + \omega y)(x + \omega^\sigma y).$$

Let $(a) = N_{K/\mathbf{Q}}\mathfrak{a}$. Then $a \in A(D, m)$. Since the ideal divisor (Inhalt) of the polynomial $x + \omega y$ is equal to $\mathfrak{a}^{-1}$, the rational quadratic form $a(x + \omega y)(x + \omega^\sigma y)$ must be primitive. Denote this form by $ax^2 + bxy + cy^2$. Then $D = b^2 - 4ac$ and we have

$$p = \frac{ax^2 + bxy + cy^2}{a},$$

where $x \equiv 1$, $y \equiv 0 \bmod m$, since $\alpha \equiv 1 \bmod m$ and g.c.d.$(a, m) = 1$.

Conversely suppose that $p \in H(D, m, a)$, where $D = b^2 - 4ac$ and $a \in A(D, m)$. Let $\alpha = x + \omega y$, where $\omega = (b + \sqrt{b^2 - 4ac})/2a \in K$. Then $\alpha \in S'_K(m)$ and $p = N_{K/\mathbf{Q}}\alpha$. Compare the decomposition of the both sides to prime ideals. Then we see that there exists a prime ideal $\mathfrak{p}$ and an integral ideal $\mathfrak{a}$ of K such that $(p) = N_{K/\mathbf{Q}}\mathfrak{p}$, $\mathfrak{p} = (\alpha)\mathfrak{a}^{1-\sigma}$ and $a = N_{K/\mathbf{Q}}\mathfrak{a}$. This completes the proof.

Remark 2.1. For a given pair of integers d_0 and m, the number of distinct sets $\mathfrak{N}(C'_m(\mathfrak{a}))$ is not exceed the number of the classes mod $\mathfrak{S}'_K(m)$. Hence the set of rational primes decomposed completely in $\hat{L}_m/\mathbf{Q}$ coincides with the union of rational primes contained in $H(D, m, a)$ by a finite number of rational integers a satisfying the condition (2.3) and $\left(\frac{d_1}{a}\right) = 1$.

Remark 2.2. The set of rational primes decomposed completely in $\hat{L}_m/\mathbf{Q}$ coincides also with the set of primes p such that $[d_1, d_2, p] = 1$, where the symbol is defined in [2]. On a treatment by means of this symbol in a restricted case, see [4, Proposition 3.1].

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