Abstract

Let \((R, \mathfrak{m})\) be a Noetherian local ring, \(\mathfrak{a}\) an ideal of \(R\) and \(M\) a finitely generated \(R\)-module. We investigate some properties of formal local cohomology modules with respect to a Serre subcategory. We provide a common language to indicate some properties of formal local cohomology modules.

1. Introduction

Throughout this paper \((R, \mathfrak{m})\) is a commutative Noetherian local ring, \(\mathfrak{a}\) an ideal of \(R\) and \(M\) is a finitely generated \(R\)-module. For an integer \(i \in \mathbb{N}_0\), \(H^i_\mathfrak{a}(N)\) denotes the \(i\)-th local cohomology module of \(M\) with respect to \(\mathfrak{a}\) as introduced by Grothendieck (cf. [1], [2]).

We shall consider the family of local cohomology modules \(\{H^i_\mathfrak{m}\left(\frac{M}{\mathfrak{a}^nM}\right)\}_{n \in \mathbb{N}}\) for a non-negative integer \(i \in \mathbb{N}_0\). With natural homomorphisms, this family forms an inverse system. Schenzel introduced the \(i\)-th formal local cohomology of \(M\) with respect to \(\mathfrak{a}\) in the form of \(f^i_\mathfrak{a}(M) := \varprojlim_{n \in \mathbb{N}} H^i_\mathfrak{m}\left(\frac{M}{\mathfrak{a}^nM}\right)\), which is the \(i\)-th cohomology module of the \(\mathfrak{a}\)-adic completion of the Čech complex \(\check{\mathcal{C}}(\mathfrak{x}) \otimes_R M\), where \(\mathfrak{x}\) denotes a system of elements of \(R\) such that \(\text{Rad}(\mathfrak{x}, R) = \mathfrak{m}\) (see [3, Definition 3.1]). He defines the formal grade as \(\text{f.grade}(\mathfrak{a}, M) = \inf \{i \in \mathbb{N}_0 \mid f^i_\mathfrak{a}(M) \neq 0\}\). For any ideal \(\mathfrak{a}\) of \(R\) and finitely generated \(R\)-module \(M\) the following statements hold:

(i) (See [3, Theorem 3.11]). If \(0 \to M' \to M \to M'' \to 0\) is a short exact sequence of finitely generated \(R\)-modules, then there is the following long exact sequence:

\[
\cdots \to f^i_\mathfrak{a}(M') \to f^i_\mathfrak{a}(M) \to f^i_\mathfrak{a}(M'') \to \cdots
\]

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*Corresponding author: taheri@khu.ac.ir*
(ii) (See [3, Theorem 1.3]). \( f.\ grade(a, M) \leq \dim(M) - cd(a, M) \); some properties of formal local cohomology have been presented in [3, 4, 5 and 6].

Throughout this paper \( S \) denotes a Serre subcategory of the category of \( R \)-modules and \( R \)-homomorphisms (we recall that a class \( S \) of \( R \)-modules is a Serre subcategory of the category of \( R \)-modules and \( R \)-homomorphisms if \( S \) is closed under taking submodules, quotients and extensions).

Our paper contains three sections. In Section 2, we shall define the formal grade of \( a \) with respect to \( M \) in \( S \) as the infimum of the integers \( i \) such that \( f_a^i(M) \notin S \) and is denoted by \( f.\ grade_S(a, M) \). (See definition 2.1). Then we shall obtain some properties of this notion. We show that if \( \Gamma_a(M) \) is a pure submodule of \( M \), then \( \Hom_R(\frac{R}{m}, f_a^i(\Gamma_a(M))) \) and \( \Hom_R(\frac{R}{m}, f_a^{i-1}(\frac{M}{\Gamma_a(M)})) \) belong to \( S \), where \( t = f.\ grade_S(a, M) \).

In Section 3, we shall define the formal cohomological dimension of \( a \) with respect to \( M \) in \( S \) as the supremum of the integers \( i \) such that \( f_a^i(M) \notin S \) and is denoted by \( f.\ cd_S(a, M) \). (See definition 3.1). The main result of this section is that if \( f_a^i(M) \in S \) and \( H_m^i(M) \in S \) for all \( i > t \), then \( \frac{R}{a} \otimes_R f_a^i(M) \) belongs to \( S \).

### 2. The formal grade of a module in a Serre subcategory

**Definition 2.1.** The formal grade of \( a \) with respect to \( M \) in \( S \) is the infimum of the integers \( i \) such that \( f_a^i(M) \notin S \) and is denoted by \( f.\ grade_S(a, M) \).

**Proposition 2.2.** Let \((R, m)\) be a local ring and \( a \) be an ideal of \( R \). If \( 0 \to L \to M \to N \to 0 \) is an exact sequence of finitely generated \( R \)-modules, then the following statements hold.

(a) \( f.\ grade_S(a, M) \geq \min\{f.\ grade_S(a, L), f.\ grade_S(a, N)\} \).

(b) \( f.\ grade_S(a, L) \geq \min\{f.\ grade_S(a, M), f.\ grade_S(a, N) + 1\} \).

(c) \( f.\ grade_S(a, N) \geq \min\{f.\ grade_S(a, L) - 1, f.\ grade_S(a, M)\} \).

**Proof.** According to [3, Theorem 3.11], the above short exact sequence induces the following long exact sequence.

\[ \cdots \to f_a^{i-1}(N) \to f_a^i(L) \to f_a^i(M) \to f_a^i(N) \to f_a^{i+1}(L) \to \cdots \]

So, the result follows.
Corollary 2.3. If $\underline{x} = x_1, ..., x_n$ is a regular $M$-sequence, then $f.\text{grade}_S \left( a, \frac{M}{\Sigma M} \right) \geq f.\text{grade}_S (a, M) - n$.

Proof. Consider the following exact sequence ($n \in \mathbb{N}$)
\[
0 \to M \xrightarrow{x_n} (x_1, ..., x_n)M \xrightarrow{nats} M \to (x_1, ..., x_n)M \to 0
\]
whenever $n = 1$ by $(x_1, ..., x_n)M$ we mean 0.

Corollary 2.4. Let $a$ and $b$ be ideals of $R$. Then

(a) $f.\text{grade}_S (a \cap b, M) \geq \min \{f.\text{grade}_S (a, M), f.\text{grade}_S (b, M), f.\text{grade}_S ((a, b), M) + 1 \}$.

(b) $f.\text{grade}_S ((a, b), M) \geq \min \{f.\text{grade}_S (a \cap b, M) - 1, f.\text{grade}_S (a, M), f.\text{grade}_S (b, M) \}$.

Proof. For all $n \in \mathbb{N}$ there is a short exact sequence as follows:
\[
0 \to \frac{M}{a^nM} \to \frac{M}{(a \cap b)^nM} \oplus \frac{M}{b^nM} \to \frac{M}{(a^n, b^n)M} \to 0.
\]
By using [3,Theorem 5.1], the above exact sequence induces the following long exact sequence.
\[
\cdots \to \lim_{\to \left( M \right)} \frac{H^i_m(M)}{(a \cap b)^nM} \oplus \lim_{\to \left( M \right)} \frac{H^i_m(M)}{a^nM} \oplus \lim_{\to \left( M \right)} \frac{H^i_m(M)}{b^nM} \to \lim_{\to \left( M \right)} \frac{H^i_m(M)}{(a \cap b)^nM} \to \cdots
\]
So by using an argument similar to that of Proposition 2.2, the result follows.

Corollary 2.5. Assume that $M$ is a finitely generated $R$-module and $N_1$ and $N_2$ are submodules of $M$. Then considering the exact sequence $0 \to \frac{M}{N_1 \cap N_2} \to \frac{M}{N_1} \oplus \frac{M}{N_2} \to \frac{M}{N_1 + N_2} \to 0$ we shall have

(a) $f.\text{grade}_S (a, \frac{M}{N_1 \cap N_2}) \geq \min \{f.\text{grade}_S (a, \frac{M}{N_1}), f.\text{grade}_S (a, \frac{M}{N_2}), f.\text{grade}_S (a, \frac{M}{N_1 + N_2}) - 1\}$.

(b) $f.\text{grade}_S (a, \frac{M}{N_1 \cap N_2}) \geq \min \{f.\text{grade}_S (a, \frac{M}{N_1}), f.\text{grade}_S (a, \frac{M}{N_2}), f.\text{grade}_S (a, \frac{M}{N_1 + N_2}) - 1\}$.

Theorem 2.6. Let $a$ be an ideal of a local ring $(R, m)$, $M$ be a finitely generated $R$-module and $L$ be a pure submodule of $M$. Then $f.\text{grade}_S (a, L) \geq f.\text{grade}_S (a, M)$ where $S$ is a Serre subcategory of the category of $R$-modules and $R$-homomorphisms. In particular, $\inf \{ \inf \left( H^i_m(L) \in S \right) \} \geq \inf \{ \inf \left( H^i_m(M) \notin S \right) \}$. 

339
Proof. Let $L$ be a pure submodule of $M$. So $\frac{L}{a^nL} \to \frac{M}{a^nM}$ is pure for each $n \in \mathbb{N}$. Now according to [8, Corollary 3.2 (a)], $H^i_m\left(\frac{L}{a^nL}\right) \to H^i_m\left(\frac{M}{a^nM}\right)$ is injective. Since inverse limit is a left exact functor, $f^i_a(L)$ is isomorphic to a submodule of $f^i_a(M)$. Consequently, $f.g._S(a, L) \geq f.g._S(a, M)$. If $a = 0$ then, $f.g._S(0, M) = \inf \{i | H^i_m(M) \notin S\}$ and the result follows.

Corollary 2.7. If $0 \to L \to M \to N \to 0$ is a pure exact sequence of finitely generated $R$-modules, then $\min \{f.g._S(a, L), f.g._S(a, N) + 1\} \geq f.g._S(a, M)$.

Proof. Since $L$ is a pure submodules of $M$, as a result of the previous theorem, $f.g._S(a, L) \geq f.g._S(a, M)$. Hence we must prove that $f.g._S(a, N) + 1 \geq f.g._S(a, M)$. We assume that $i < f.g._S(a, M)$ and we show that $i < f.g._S(a, N) + 1$. Consider the following long exact sequence.

$$\ldots \to f^{i-1}_a(M) \to f^i_a(N) \to f^i_a(L) \to f^i_a(M) \to f^i_a(N) \to \ldots \ (*)$$

If $i < f.g._S(a, M)$, then $f^i_a(M), f^{i-1}_a(M), \ldots, f^0_a(L) \in S$. On the other hand, since $i < f.g._S(a, L), f^i_a(L) \in S$. Hence, it follows from $(*)$ that $f^i_a(N), \ldots, f^{i-1}_a(N) \in S$ and so $i - 1 < f.g._S(a, N)$.

Theorem 2.8. Let $(R, m)$ be a local ring, $a$ be an ideal of $R$, $S$ be a Serre subcategory of the category of $R$-modules and $R$-homomorphisms and $M \in S$ be a finitely generated $R$-module such that $\Gamma_a(M)$ is a pure submodule of $M$. Then $\text{Hom}_R\left(\frac{R}{a^t}, f_a^i(\Gamma_a(M))\right) \in S$, where $t = f.g._S(a, M)$.

Proof. Due to the previous theorem, $f.g._S(a, \Gamma_a(M)) \geq f.g._S(a, M)$. If $f.g._S(a, \Gamma_a(M)) > f.g._S(a, M)$, then the result is obvious. Accordingly, we assume that $f.g._S(a, \Gamma_a(M)) = f.g._S(a, M)$. We know that $\text{Supp}(\Gamma_a(M)) \subseteq \text{Var}(a)$. By using [4, Lemma 2.3], $f^i_a(\Gamma_a(M)) \equiv H^i_m(\Gamma_a(M))$ for all $i \geq 0$. So, if $j < f.g._S(a, M)$, then $f^j_a(\Gamma_a(M)) \equiv H^j_m(\Gamma_a(M)) \in S$ and $\text{Ext}_R^k\left(\frac{R}{m}, H^j_m(\Gamma_a(M))\right) \in S$ for all $k \geq 0$ and $j < f.g._S(a, M)$. Moreover $\text{Ext}_R^k\left(\frac{R}{m}, \Gamma_a(M)\right) \in S$, because $\Gamma_a(M) \in S$. Consequently, according to [7, Theorem 2.2], $\text{Hom}_R\left(\frac{R}{m}, H^m_m(\Gamma_a(M))\right) \in S$, where $t = f.g._S(a, M)$.

Corollary 2.9 With the same notations as Theorem 2.8, let $X \in S$ be a submodule of $f_a^i(\Gamma_a(M))$, where $t = f.g._S(a, M)$. Then $\text{Hom}_R\left(\frac{R}{m}, \frac{f_a^i(\Gamma_a(M))}{X}\right) \in S$.

Proof. Consider the long exact sequence:
In accordance with the previous theorem $\Hom_R \left( \frac{R}{m}, f_t^a(\Gamma_a(M)) \right) \rightarrow \Hom_R \left( \frac{R}{m}, \frac{f_t^a(\Gamma_a(M))}{x} \right) \rightarrow \Ext^1_R \left( \frac{R}{m}, X \right) \rightarrow 0$. Moreover $\Ext^1_R \left( \frac{R}{m}, X \right) \in S$. It follows from the exact sequence (*) that $\Hom_R \left( \frac{R}{m}, \frac{f_t^a(\Gamma_a(M))}{x} \right) \in S$.

**Theorem 2.10.** Suppose that $a$ is an ideal of $(R, m)$ and $M \in S$ is a finitely generated $R$-module such that $\Gamma_a(M)$ is a pure submodule of $M$. Then $\Hom_R \left( \frac{R}{m}, f^{t-1}_a \left( \frac{M}{\Gamma_a(M)} \right) \right) \in S$, where $t = f \cdot \text{grade}_S(a, M)$.

**Proof.** One has $f \cdot \text{grade}_S(a, \Gamma_a(M)) \geq f \cdot \text{grade}_S(a, M)$, by Theorem 2.6. Now, the exact sequence $0 \to \Gamma_a(M) \to M \to \frac{M}{\Gamma_a(M)} \to 0$ induces the following long exact sequence:

$$\ldots \to f^{t-1}_a(\Gamma_a(M)) \xrightarrow{\alpha} f^{t-1}_a(M) \xrightarrow{\beta} f^{t-1}_a \left( \frac{M}{\Gamma_a(M)} \right) \xrightarrow{\gamma} f^{t-1}_a(\Gamma_a(M)) \xrightarrow{\delta} \ldots \quad (*)$$

Using the exact sequence (*), we obtain the short exact sequence $0 \to \text{Im}(\beta) \to f^{t-1}_a(M) \to \text{Im}(\gamma) \to 0$. Since $f^{t-1}_a(M) \in S$, $\text{Im}(\beta) \in S$ and $\text{Im}(\gamma) \in S$.

Furthermore, we have the exact sequence $0 \to \text{Im}(\xi) \to H^t_m(\Gamma_a(M)) \to \text{Im}(\varphi) \to 0$ which induces the following long exact sequence:

$$0 \to \Hom_R \left( \frac{R}{m}, \text{Im}(\xi) \right) \to \Hom_R \left( \frac{R}{m}, H^t_m(\Gamma_a(M)) \right) \to \ldots.$$ 

Thus $\Hom_R \left( \frac{R}{m}, \text{Im}(\xi) \right) \in S$. Finally, by considering the short exact sequence $0 \to \text{Im}(\gamma) \to f^{t-1}_a \left( \frac{M}{\Gamma_a(M)} \right) \to \text{Im}(\xi) \to 0$ we can conclude that $\Hom_R \left( \frac{R}{m}, f^{t-1}_a \left( \frac{M}{\Gamma_a(M)} \right) \right) \in S$.

**Theorem 2.11.** Suppose that $R$ is complete with respect to the $a$–adic topology and $M \in S$ be a finitely generated $R$-module and $t$ a positive integer such that $f_t^a(M) \in S$ for all $i < t$. Then $\Hom_R \left( \frac{R}{m}, f_t^a(M) \right) \in S$.

**Proof.** We use induction on $t$. Let $t=0$. Consider the following isomorphisms.

$$\Hom \left( \frac{R}{m}, f_0^a(M) \right) \cong \lim_{\leftarrow n} \Hom \left( \frac{R}{m}, H^0_n(\frac{M}{a^n M}) \right) \cong \lim_{\leftarrow n} \Hom \left( \frac{R}{m}, \frac{M}{a^n M} \right) \cong \Hom \left( \frac{R}{m}, \lim_{\leftarrow n} \frac{M}{a^n M} \right) \cong \Hom \left( \frac{R}{m}, M \right)$$
It is clear that $\text{Hom}_R(\frac{R}{m}, M) \in S$. So by the above isomorphisms, we deduce that 

$$\text{Hom}_R(\frac{R}{m}, f^1_a(M)) \in S.$$

Suppose that $t>0$ and the result is true for all integer $i$ less than $t$. Set $N := I_m(M)$. Then $f^i_a(M) \cong f^i_a(M/N)$ for all $i > 0$, and so we may assume that $\text{depth}_R(M) > 0$. There is an $M$-regular element $x \in m$. The exact sequence $0 \to M \xrightarrow{x} M \to \frac{M}{xM} \to 0$ induces the following long exact sequence:

$$\cdots \to f^{t-2}_a(M) \xrightarrow{x} f^{t-2}_a(M) \xrightarrow{f} f^{t-2}_a(\frac{M}{xM})$$

$$\to f^{t-1}_a(M) \xrightarrow{x} f^{t-1}_a(M) \xrightarrow{g} f^{t-1}_a(\frac{M}{xM})$$

$$\to f^t_a(M) \xrightarrow{x} f^t_a(M) \xrightarrow{h} \cdots. \quad (*)$$

Using the exact sequence $(*)$ we obtain the short exact sequence

$$0 \to f^{t-1}_a(M)_{\text{xf}} \to f^t_a(M)_{\text{xf}} \to (0 : x) \to 0.$$

Now, this exact sequence induces the following long exact sequence:

$$0 \to \text{Hom}_R(\frac{R}{m}, f^{t-1}_a(M)) \to \text{Hom}_R(\frac{R}{m}, f^t_a(M)) \to \text{Hom}_R(\frac{R}{m}, (0 : x)) \to$$

$$\text{Ext}_R^1(\frac{R}{m}, f^{t-1}_a(M)) \to \cdots. \quad (**)$$

By using $(*)$, $f^i_a(M) \in S$ for all $i < t - 1$. Therefore by the induction hypothesis $\text{Hom}_R(\frac{R}{m}, f^{t-1}_a(M)) \in S$. Furthermore $\text{Ext}_R^1(\frac{R}{m}, f^{t-1}_a(M)) \in S$ because $f^{t-1}_a(M) \in S$. Thus in accordance with $(**)$, $\text{Hom}_R(\frac{R}{m}, (0 : x)) \in S$. Since $x \in m$ according to [9,10.86] we have the following isomorphisms.

$$\text{Hom}_R(\frac{R}{m}, (0 : x)) \cong \text{Hom}_R(\frac{R}{m}, \text{Hom}_R(\frac{R}{xR}, f^t_a(M))) \cong$$

$$\text{Hom}_R(\frac{R}{m} \otimes_R \frac{R}{xR}, f^t_a(M)) \cong \text{Hom}_R(\frac{R}{m}, f^t_a(M)).$$

Consequently $\text{Hom}_R(\frac{R}{m}, f^t_a(M)) \in S$. 

342
3. The formal cohomological dimension in a Serre subcategory

We recall from [3, Theorem 1.1] that for a finitely generated $R$-module $M$, $\sup \{ i \in \mathbb{N}_0 | f^i_a(M) \neq 0 \} = \dim \left( \frac{M}{aM} \right)$.

**Definition 3.1.** The formal cohomological dimension of $M$ with respect to $a$ in $S$ is the supremum of the integers $i$ such that $f^i_a(M) \in S$ and is denoted by $f.c.d._S(a, M)$.

**Theorem 3.2.** Suppose that $S$ is a Serre subcategory of the category of $R$-modules and $R$-homomorphisms and $L$ and $N$ are two finitely generated $R$-modules such that $\text{Supp}_R(L) \subseteq \text{Supp}_R(N)$. Then $f.c.d._S(a, L) \leq f.c.d._S(a, N)$.

**Proof.** It is enough to prove that $f^i_a(L) \in S$ for all $i > f.c.d._S(a, N)$ and all finitely generated $R$-module $L$ such that $\text{Supp}_R(L) \subseteq \text{Supp}_R(N)$. We use descending induction on $i$. For all $i > \dim \left( \frac{L}{aL} \right) + f.c.d._S(a, N)$, $f^i_a(L) = 0 \in S$. Let $i > f.c.d._S(a, N)$ and the result is proved for $i + 1$. By Gruson’s theorem, there is a chain $0 = L_0 \subseteq L_1 \subseteq \cdots \subseteq L_l = L$ of submodules of $L$ such that $\frac{L_i}{L_{i-1}}$ is a homomorphic image of a direct sum of finitely many copies of $N$. Consider the exact sequence $0 \to L_{i-1} \to L_i \to \frac{L_i}{L_{i-1}} \to 0 \quad (i = 0, 1, \ldots, l)$. We may assume that $l = 1$. The exact sequence $0 \to K \to \bigoplus_{j=1}^t N \to L \to 0$ where $K$ is a finitely generated $R$-module induces the following long exact sequence:

$$\cdots \to f^i_a(\bigoplus_{j=1}^t N) \to f^i_a(L) \to f^{i+1}_a(K) \to \cdots \quad (*)$$

Based on the induction hypothesis $f^{i+1}_a(K) \in S$. Moreover $f^i_a(\bigoplus_{j=1}^t N) = \bigoplus_{j=1}^t f^i_a(N) \in S$ for all $i > f.c.d._S(a, N)$, hence it follows from the exact sequence $(*)$ that $f^i_a(L) \in S$.

The next example shows that even if $\text{Supp}_R(M) = \text{Supp}_R(N)$, then it may not true that $f\text{-grade}_S(a, M) = f\text{-grade}_S(a, N)$.

**Example 3.3.** (See [4, Example 4.3 (i)]) Let $(R, \mathfrak{m})$ be a 2 dimensional complete regular local ring, $\mathcal{S} = 0$ and $\mathfrak{a}$ be an ideal of $R$ with $\dim \left( \frac{R}{\mathfrak{a}} \right) = 1$. Then by using [5, Theorem 1.1], $f\text{-grade}_S(a, R) = 1$ and $f\text{-grade}_S(\frac{R}{\mathfrak{a}}) = 0$. Set $M := R \oplus \frac{R}{\mathfrak{m}}$. Then $\text{Supp}_R(M) = \text{Supp}_R(R)$. But $f\text{-grade}_S(a, M) = \inf \left\{ f\text{-grade}_S(a, R), f\text{-grade}_S(\frac{R}{\mathfrak{m}}) \right\} = 0$.

**Corollary 3.4.** For all $x \in a \cdot f.c.d._S(a, M) \geq f.c.d._S(a, \frac{M}{xM})$.

**Corollary 3.5.** Suppose that $0 \to L \to M \to N \to 0$ is an exact sequence of finitely generated $R$-modules. Then $f.c.d._S(a, M) = \max \{ f.c.d._S(a, L), f.c.d._S(a, N) \}$.
Proof. Since $\text{Supp}_R(M) = \text{Supp}_R(L) \cup \text{Supp}_R(N)$ by referring to Theorem 3.2 we deduce that $f \cdot c_{d_S}(a, M) \geq f \cdot c_{d_S}(a, L)$ and $f \cdot c_{d_S}(a, M) \geq f \cdot c_{d_S}(a, N)$. Therefore $f \cdot c_{d_S}(a, M) \geq \max \{f \cdot c_{d_S}(a, L), f \cdot c_{d_S}(a, N)\}$.

Next we prove that $\max \{f \cdot c_{d_S}(a, L), f \cdot c_{d_S}(a, N)\} \geq f \cdot c_{d_S}(a, M)$.

Let $i > \max \{f \cdot c_{d_S}(a, L), f \cdot c_{d_S}(a, N)\}$. Then $f^i_a(N), f^i_a(L) \in S$ and from the exact sequence $f^i_a(L) \to f^i_a(M) \to f^i_a(N)$ we conclude that $f^i_a(M) \in S$. Thus, $\max\{f \cdot c_{d_S}(a, L), f \cdot c_{d_S}(a, N)\} \geq f \cdot c_{d_S}(a, M)$.

We recall that the cohomological dimension of an $R$-module $M$ with respect to an ideal $a$ of $R$ in $S$ is defined as

$$c_{d_S}(a, M) := \sup \{i \in \mathbb{N} | H^i_a(M) \notin S\}.$$ 

The following lemma shows that when we considering the Artinianness of $f^i_a(M)$, we can assume that $M$ is $a$-torsion-free.

Lemma 3.6. Suppose that $a$ is an ideal of a local ring $(R, m)$ and $t$ be a non-negative integer. If $H^i_m(M) \in S$ for all $i \geq t$, then the following are equivalent:

(a) $f^i_a(M) \in S$ for all $i \geq t$.
(b) $f^i_a\left(\frac{M}{\Gamma_a(M)}\right) \in S$ for all $i \geq t$.

Proof. According to the hypothesis $t > c_{d_S}(m, M)$. On the other hand $\text{Supp}_R(\Gamma_a(M)) \subseteq \text{Supp}_R(M)$. So by referring to [7, Theorem 3.5], $c_{d_S}(m, \Gamma_a(M)) \leq c_{d_S}(m, M)$. Thus, $t > c_{d_S}(m, \Gamma_a(M))$ and $H^i_m(\Gamma_a(M)) \in S$ for all $i \geq t$. Now, consider the following long exact sequence:

$$\cdots \to f^i_a(\Gamma_a(M)) \to f^i_a(M) \to f^i_a\left(\frac{M}{\Gamma_a(M)}\right) \to f^{i+1}_a(\Gamma_a(M)) \to \cdots. (\ast)$$

According to [4, Lemma 2.3] $f^i_a(\Gamma_a(M)) \cong H^i_m(\Gamma_a(M))$. By using the hypothesis $f^i_a(\Gamma_a(M)) \in S$ for all $i \geq t$. So it follows from the exact sequence $(\ast)$ that $f^i_a(M) \in S$ if and only if $f^i_a\left(\frac{M}{\Gamma_a(M)}\right) \in S$ for all $i \geq t$.

Theorem 3.7. Let $(R, m)$ be a local ring and $M \in S$ be a finitely generated $R$-module of dimension d such that $c_{d_S}(m, M) \leq f \cdot c_{d_S}(a, M)$. Then $\frac{f^i_a(M)}{a f^i_a(M)} \in S$ where $t = f \cdot c_{d_S}(a, M)$.

Proof. We use induction on $d = \dim (M)$. If $d = 0$, then $\dim\left(\frac{M}{aM}\right) = 0$. Accordingly to [3, Theorem 1.1], $f^i_a(M) = 0$ for all $i > 0$. 

344
Moreover $f^0_a(M) \cong M \in S$. By definition $H^i_m(M) \in S$ for all $i > t$. Therefore from the above lemma we can assume that $M$ is a-torsion-free and there is an $M$-regular element $x \in a$. Consider the long exact sequence:

$$\cdots \to f^i_a(M) \xrightarrow{x} f^i_a(M) \xrightarrow{f} f^i_a(M) \xrightarrow{g} f^{i+1}_a(M) \xrightarrow{h} \cdots. \tag{*}$$

By using the hypothesis $f^i_a(M) \in S$ for all $i > t$ (because $t = f \cdot \text{cd}_S(a, M)$). So using the above long exact sequence $f^i_a(M) \in S$ for all $i > t$. By induction hypothesis, $\frac{f^i_a(M)}{af^i_a(M)} \in S$ because $\dim\left(\frac{M}{xM}\right) = \dim(M) - 1$.

Afterwards from the exact sequence (\textit{*}) we get the following short exact sequence.

$$0 \to \text{Im}(f) \to f^t_a\left(\frac{M}{xM}\right) \to \text{Im}(g) \to 0.$$

So we obtain the following long exact sequence:

$$\cdots \to \text{Tor}^R_1\left(\frac{R}{a}, \text{Im}(g)\right) \to \text{Im}(f) \to f^t_a\left(\frac{M}{xM}\right) \to \frac{\text{Im}(g)}{af^t_a(M)} \to 0.$$ 

Since $f^t_a(M) \in S$ and $\text{Im}(g)$ is a submodule of $f^{t+1}_a(M)$, we deduce that $\text{Tor}^R_1\left(\frac{R}{a}, \text{Im}(g)\right) \in S$. On the other hand, $\frac{f^t_a(M)}{af^t_a(M)} \in S$. Therefore, $\frac{\text{Im}(f)}{af^t_a(M)} \in S$ by the above long exact sequence.

Now, consider the following long exact sequence.

$$\frac{f^t_a(M)}{af^t_a(M)} \xrightarrow{x} f^t_a(M) \xrightarrow{f} f^t_a(M) \xrightarrow{g} f^{t+1}_a(M) \xrightarrow{h} \cdots.$$

So, $\frac{f^t_a(M)}{af^t_a(M)} \cong \frac{\text{Im}(f)}{af^t_a(M)}$ because $x \in a$. Consequently, $\frac{f^t_a(M)}{af^t_a(M)} \in S$.

**Proposition 3.8.** For a finitely generated $R$-module $M$,

$$f \cdot \text{cd}_S(a, M) = \max\{f \cdot \text{cd}_S(a, R_P) | P \in \text{Ass}_R(M)\}.$$

**Proof.** Set $N := \bigoplus_{P \in \text{Ass}_R(M)} R_P$. Then $\text{Supp}_R(M) = \text{Supp}_R(N)$. So, by Theorem 3.2 and Corollary 3.5, $f \cdot \text{cd}_S(a, M) = f \cdot \text{cd}_S(a, N) = \max\{f \cdot \text{cd}_S(a, R_P) | P \in \text{Ass}_R(M)\}$.

**Proposition 3.9.** Assume that $a$ is an ideal of the local ring $(R, m)$. Then $\text{Hom}_R\left(\frac{R}{m}, f^0_a(M)\right) \in S$ if and only if $\text{Hom}_R\left(\frac{R}{m}, M\right) \in S$.

**Proof.** It is enough to consider the following isomorphisms

$$\text{Hom}_R\left(\frac{R}{m}, f^0_a(M)\right) \cong \text{Hom}_R\left(\frac{R}{m}, f^0_a(M)\right) \cong \text{Hom}_R\left(\frac{R}{m}, M\right) \cong \text{Hom}_R\left(\frac{R}{m}, M\right).$$
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References