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Article

A Proof of the Riemann Hypothesis Based on a New Expression of the Completed Zeta Function

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Abstract: The Riemann Hypothesis (RH) is proved based on a new expression of the completed zeta function $\xi(s)$, which was obtained through pairing the conjugate zeros ρ_i and $\bar{\rho}_i$ in the Hadamard product, with consideration of the multiplicity of zeros, i.e.,

$$\xi(s) = \xi(0) \prod_{\rho} \left(1 - \frac{s}{\rho}\right) = \xi(0) \prod_{i=1}^{\infty} \left(1 - \frac{s}{\rho_i}\right) \left(1 - \frac{s}{\bar{\rho}_i}\right) = \xi(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)^{m_i}$$

where $\xi(0) = \frac{1}{2}$, $\rho_i = \alpha_i + j\beta_i$, $\bar{\rho}_i = \alpha_i - j\beta_i$, with $0 < \alpha_i < 1$, $\beta_i \neq 0$, $0 < |\beta_1| \leq |\beta_2| \leq \dots$, and $m_i \geq 1$ is the multiplicity of ρ_i . Then, according to the functional equation $\xi(s) = \xi(1-s)$, we have

$$\prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} = \prod_{i=1}^{\infty} \left(1 + \frac{(1-s - \alpha_i)^2}{\beta_i^2}\right)^{m_i}$$

Due to the divisibility contained in the above equation and the uniqueness of m_i , each polynomial factor can only divide (and thus equal) the corresponding factor on the opposite side of the equation. Therefore, we obtain

$$\left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} = \left(1 + \frac{(1-s - \alpha_i)^2}{\beta_i^2}\right)^{m_i}, i = 1, 2, 3, \dots$$

which is further equivalent to

$$\alpha_i = \frac{1}{2}, 0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots, i = 1, 2, 3, \dots$$

Thus, we conclude that the RH is true.

Keywords: Riemann Hypothesis; Hadamard product; New expression of the completed zeta function

1. Introduction

The RH [1] is one of the most important unsolved problems in mathematics. Although there are many achievements towards proving this celebrated hypothesis, it remains an open problem [2,3]. The Riemann zeta function is originally defined in the half-plane $\Re(s) > 1$ by the absolutely convergent series [2]

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \Re(s) > 1 \quad (1)$$

The connection between the above-defined Riemann zeta function and prime numbers was discovered by Euler, i.e., the famous Euler product

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} = \prod_p (1 - p^{-s})^{-1}, \Re(s) > 1 \quad (2)$$

where p runs over the prime numbers.

Riemann showed in his paper in 1859 how to extend the zeta function to the whole complex plane $\mathbb{C}$ by analytic continuation, i.e.,

$$\zeta(s) = \frac{\Gamma(1-s)}{2\pi i} \int_{\infty}^{\infty} \frac{(-x)^s}{e^x - 1} \cdot \frac{dx}{x} \quad (3a)$$

where " $\int_{\infty}^{\infty}$ " is the symbol adopted by Riemann to represent the contour integral from $+\infty$ to $+\infty$ around a domain which includes the value 0 but no other point of discontinuity of the integrand in its interior.

Or equivalently,

$$\zeta(s) = \frac{\pi^{s/2}}{\Gamma(s/2)} \left\{ \frac{1}{s(s-1)} + \int_1^{\infty} (x^{\frac{s}{2}-1} + x^{-\frac{s}{2}-\frac{1}{2}}) \cdot \left(\frac{\theta(x)-1}{2} \right) dx \right\} \quad (3b)$$

where $\theta(x) = \sum_{n=-\infty}^{\infty} e^{-n^2\pi x}$ is the Jacobi theta function, Γ is the Gamma function in the following Weierstrass expression

$$\frac{1}{\Gamma(s)} = s \cdot e^{\gamma s} \prod_{n=1}^{\infty} \left(1 + \frac{s}{n} \right) e^{-s/n} \quad (4)$$

where γ is the Euler-Mascheroni constant.

As shown by Riemann, $\zeta(s)$ extends to $\mathbb{C}$ as a meromorphic function with only a simple pole at $s = 1$, with residue 1, and satisfies the following functional equation

$$\pi^{-\frac{s}{2}} \Gamma\left(\frac{s}{2}\right) \zeta(s) = \pi^{-\frac{1-s}{2}} \Gamma\left(\frac{1-s}{2}\right) \zeta(1-s) \quad (5)$$

The Riemann zeta function $\zeta(s)$ has zeros at the negative even integers: $-2, -4, -6, -8, \dots$ and one refers to them as the **trivial zeros**. The other zeros of $\zeta(s)$ are the complex numbers, i.e., **non-trivial zeros** [2].

In 1896, Hadamard [4] and Poussin [5] independently proved that no zeros could lie on the line $\Re(s) = 1$, together with the functional equation $\zeta(s) = \zeta(1-s)$ and the fact that there are no zeros with real part greater than 1, this showed that all non-trivial zeros must lie in the interior of the **critical strip** $0 < \Re(s) < 1$. Later on, Hardy (1914) [6], Hardy and Littlewood (1921) [7] showed that there are infinitely many zeros on the **critical line** $\Re(s) = \frac{1}{2}$.

To give a summary of the related research works on the RH, we have the following results on the properties of the non-trivial zeros of $\zeta(s)$ [4-9].

Lemma 1. *Non-trivial zeroes of $\zeta(s)$, noted as $\rho = \alpha + j\beta$, have the following properties*

- 1) *The number of non-trivial zeroes is infinity;*
- 2) *$\beta \neq 0$;*
- 3) *$0 < \alpha < 1$;*
- 4) *$\rho, \bar{\rho}, 1 - \bar{\rho}, 1 - \rho$ are all non-trivial zeroes.*

As further study, the completed zeta function $\xi(s)$ is proposed, i.e.,

$$\xi(s) = \frac{1}{2} s(s-1) \pi^{-\frac{s}{2}} \Gamma\left(\frac{s}{2}\right) \zeta(s) \quad (6)$$

It is well-known that $\xi(s)$ is an entire function of order 1. This implies $\xi(s)$ is analytic, and can be expressed as infinite product of polynomial factors, in the whole complex plane $\mathbb{C}$. In addition, replacing s with $1-s$ in Eq.(6), and combining Eq.(5), we obtain the following functional equation

$$\xi(s) = \xi(1-s) \quad (7)$$

According to the definition of $\zeta(s)$, and recalling Eq.(4), the trivial zeros of $\zeta(s)$ are canceled by the poles of $\Gamma(\frac{s}{2})$. The zero of $s - 1$ and the pole of $\zeta(s)$ cancel; the zero $s = 0$ and the pole of $\Gamma(\frac{s}{2})$ cancel [9-11]. Thus, all zeros of $\zeta(s)$ are exactly the nontrivial zeros of $\zeta(s)$. Then we have the following Lemma 2.

Lemma 2. *The zeros of $\zeta(s)$ coincide with the non-trivial zeros of $\zeta(s)$.*

Consequently, the following two statements are equivalent.

Statement 1: All the non-trivial zeros of $\zeta(s)$ have real part equal to $\frac{1}{2}$.

Statement 2: All zeros of $\zeta(s)$ have real part equal to $\frac{1}{2}$.

To prove the RH, a natural thinking is to estimate the numbers of non-trivial zeros of $\zeta(s)$ inside or outside some certain areas according to Argument Principle. Along this train of thought, there are many research works. Let $N(T)$ denote the number of non-trivial zeros of $\zeta(s)$ inside the rectangle: $0 < \alpha < 1, 0 < \beta \leq T$, and let $N_0(T)$ denote the number of non-trivial zeros of $\zeta(s)$ on the line $\alpha = \frac{1}{2}, 0 < \beta \leq T$. Selberg proved that there exist positive constants c and T_0 , such that $N_0(T) > cN(T), (T > T_0)$ [12], later on, Levinson proved that $c \geq \frac{1}{3}$ [13], Lou and Yao proved that $c \geq 0.3484$ [14], Conrey proved that $c \geq \frac{2}{5}$ [15], Bui, Conrey and Young proved that $c \geq 0.41$ [16], Feng proved that $c \geq 0.4128$ [17], Wu proved that $c \geq 0.4172$ [18].

On the other hand, many non-trivial zeros have been calculated by hand or by computer programs. Among others, Riemann found the first three non-trivial zeros [19]. Gram found the first 15 zeros based on Euler-Maclaurin summation [20]. Titchmarsh calculated the 138th to 195th zeros using the Riemann-Siegel formula [21-22]. Here are the first three (pairs of) non-trivial zeros: $\frac{1}{2} \pm j14.1347251$; $\frac{1}{2} \pm j21.0220396$; $\frac{1}{2} \pm j25.0108575$.

The idea of this paper is originated from Euler's work on proving the following famous equality

$$1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots = \frac{\pi^2}{6} \quad (8)$$

This interesting result is deduced by comparing the like terms of two types of infinite expressions (infinite power series and infinite product) of $\frac{\sin x}{x}$ as shown in the following

$$\frac{\sin x}{x} = 1 - \frac{x^2}{3!} + \frac{x^4}{5!} - \frac{x^6}{7!} + \cdots = (1 - \frac{x^2}{\pi^2})(1 - \frac{x^2}{4\pi^2})(1 - \frac{x^2}{9\pi^2}) \cdots \quad (9)$$

Then the author of this paper conjectured that $\zeta(s)$ should be factored into $(1 + \frac{(s-\alpha_i)^2}{\beta_i^2})$ or something like that, which was verified by pairing ρ_i and $\bar{\rho}_i$ in the Hadamard product of $\zeta(s)$, i.e., $(1 - \frac{s}{\rho_i})(1 - \frac{s}{\bar{\rho}_i}) = \frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} (1 + \frac{(s-\alpha_i)^2}{\beta_i^2})$.

The Hadamard product of $\zeta(s)$ as shown in Eq.(10) was first proposed by Riemann, however, it was Hadamard who showed the validity of this infinite product expansion [23].

$$\zeta(s) = \zeta(0) \prod_{\rho} (1 - \frac{s}{\rho}) \quad (10)$$

where $\zeta(0) = \frac{1}{2}$, ρ runs over all zeros of $\zeta(s)$.

Hadamard pointed out that to ensure the absolute convergence of the infinite product expansion, ρ and $1 - \rho$ are paired. Later in Section 4, we will show that ρ and $\bar{\rho}$ can also be paired to ensure the absolute convergence of the infinite product expansion.

2. Preliminary Lemmas

This section provides some preliminary lemmas to support the proof of the key lemma - Lemma 8 in next section.

To begin with, we introduce the ring of polynomials, denoted as $\mathbb{R}[x]$, which is defined as the set of all polynomials in x over the field of real numbers $\mathbb{R}$, i.e.,

$$\mathbb{R}[x] = \left\{ \sum_{i=0}^{\infty} a_i x^i \mid a_i \in \mathbb{R}, a_i \neq 0 \text{ for all but a finite number of } i \right\}$$

The set $\mathbb{R}[x]$ equipped with the operations $+$ (addition) and $\cdot$ (multiplication) is the ring of polynomials in x over the field $\mathbb{R}$.

The ring of polynomials is a subset of the ring of entire functions, which is defined as the set of all holomorphic functions on the whole complex plane $\mathbb{C}$, together with the operations of addition and multiplication, denoted as $\mathbb{H}(\mathbb{C})$ [24].

Both rings possess properties of divisibility, coprimality, and the greatest common divisor, denoted as "gcd". There are also differences between these two rings. Among others, polynomials have degrees, entire functions in infinite product form do not. For entire functions, their divisibility, coprimality and common factors are determined by the relationships between their zero sets [25,26].

In order to facilitate subsequent discussions, we present the following definitions.

Definition 1. Let $f(x) = \prod_{i=1}^{\infty} p_i(x)$, $p_i(x) \in \mathbb{R}[x]$, be an entire function, and $h(x) \in \mathbb{R}[x]$. We say $h(x)$ divides $f(x)$, denoted as $h(x) \mid f(x)$, if there exists an entire function $g(x) = \prod_{i=1}^{\infty} q_i(x)$, $q_i(x) \in \mathbb{R}[x]$, such that $f(x) = h(x) \cdot g(x)$.

Definition 2. Let $f(x) = \prod_{i=1}^{\infty} p_i(x)$, $p_i(x) \in \mathbb{R}[x]$, be an entire function, and $h(x) \in \mathbb{R}[x]$, a polynomial $d(x) \in \mathbb{R}[x]$ is called the greatest common divisor of $h(x)$ and $f(x)$ if: 1). $d(x) \mid h(x)$ and $d(x) \mid f(x)$; 2). For every polynomial $d_1(x) \in \mathbb{R}[x]$ that divides both $h(x)$ and $f(x)$, we have $d_1(x) \mid d(x)$.

Definition 3. Let $f(x) = \prod_{i=1}^{\infty} p_i(x)$, $p_i(x) \in \mathbb{R}[x]$, be an entire function, and $h(x) \in \mathbb{R}[x]$. We say that $h(x)$ and $f(x)$ are coprime (relatively prime) if whenever a polynomial $d(x) \in \mathbb{R}[x]$ divides both $h(x)$ and $f(x)$, then $d(x)$ must be a nonzero constant. This is denoted by $\gcd(h(x), f(x)) = 1$.

By Definition 2.1, the transitivity of divisibility for polynomials extends to entire functions represented as infinite products of polynomials. Specifically, let $f(x) = \prod_{i=1}^{\infty} p_i(x)$, $p_i(x) \in \mathbb{R}[x]$, be an entire function, and let $h_1(x), h_2(x) \in \mathbb{R}[x]$. If $h_1(x) \mid h_2(x)$ and $h_2(x) \mid f(x)$, then $h_1(x) \mid f(x)$.

To support the proof of the key lemma - Lemma 8 in next section. We need the following lemmas.

Lemma 3. Let $m(x), g_1(x), \dots, g_n(x) \in \mathbb{R}[x]$, $n \geq 2$. If $m(x)$ is irreducible (prime) and divides the product $g_1(x) \cdots g_n(x)$, then $m(x)$ divides one of the polynomials $g_1(x), \dots, g_n(x)$.

Lemma 4. Let $f(x), m(x) \in \mathbb{R}[x]$. If $m(x)$ is irreducible and $f(x)$ is any polynomial, then either $m(x)$ divides $f(x)$ or $\gcd(m(x), f(x)) = 1$.

Lemma 5. Let $m(x), g_1(x), g_2(x), \dots \in \mathbb{R}[x]$. If $m(x)$ is irreducible and divides the infinite product $\prod_{i=1}^{\infty} g_i(x)$, then $m(x)$ divides one of the polynomials $g_1(x), g_2(x), \dots$.

Remark 1. The contents of Lemma 3 and Lemma 4 can be found in many textbooks of linear algebra, modern algebra, or abstract algebra, see for example references [27-29]. Below we give the proof of Lemma 5.

Proof of Lemma 5. The proof is conducted by Transfinite Induction.

Let $P(\gamma)$ (γ is an ordinal number) be the statement:

" $m(x), g_1(x), \dots, g_\gamma(x) \in \mathbb{R}[x]$, $\gamma \geq 2$. If $m(x)$ is irreducible and divides the product $g_1(x) \cdots g_\gamma(x)$, then $m(x)$ divides one of the polynomials $g_1(x), \dots, g_\gamma(x)$ ", where $\gamma \in A$, $A = \mathbb{N} \cup \{\omega\}$ with the ordering that $n < \omega$ for all natural numbers n , ω is the smallest limit ordinal other than 0.

Base Case: $P(2)$ is an obvious fact according to Lemma 3 with $n = 2$;

Successor Case: To prove $P(\gamma) \Rightarrow P(\gamma + 1)$, we have $g_1(x) \cdots g_\gamma(x)g_{\gamma+1}(x) = g(x) \cdot g_{\gamma+1}(x)$, where $g(x) = g_1(x) \cdots g_\gamma(x)$. Then according to Lemma 3 with $n = 2$, we have $m(x) \mid g(x) \cdot g_{\gamma+1}(x) \Rightarrow m(x) \mid g(x)$ or $m(x) \mid g_{\gamma+1}(x)$. Considering $P(\gamma)$: if $m(x)$ divides $g(x)$, then $m(x)$ divides one of $g_1(x), \dots, g_\gamma(x)$, thus we know $P(\gamma) \Rightarrow P(\gamma + 1)$.

Limit Case: We need to prove $P(\gamma < \lambda) \Rightarrow P(\lambda)$, λ is any limit ordinal other than 0. For the sake of contradiction, assume that $P(\gamma < \lambda) \not\Rightarrow P(\lambda)$, i.e., $m(x)$ does not divide any polynomial $g_i(x), 1 \leq i \leq \lambda$. Then, considering $m(x)$ is irreducible with the property stated in Lemma 4, we have:

$$\begin{aligned} & m(x) \mid g_1(x) \cdots g_\gamma(x), \gamma \in \mathbb{N} \\ & \Rightarrow (\text{according to the transitive property of divisibility}) \\ & m(x) \mid g_1(x) \cdots g_\gamma \cdots g_\lambda(x) \\ & \Rightarrow (\text{by the assumption and Lemma 4}) \\ & \gcd(m(x), g_i(x)) = 1, 1 \leq i \leq \lambda \\ & \Rightarrow (\text{for any natural number } n \in \mathbb{N}, n < \lambda) \\ & \gcd(m(x), g_i(x)) = 1, i \in \mathbb{N} \end{aligned}$$

which contradicts $P(\gamma < \lambda) : m(x) \mid g_1(x) \cdots g_\gamma(x) \Rightarrow m(x)$ divides one of the polynomials $g_1(x), \dots, g_\gamma(x), \gamma \in \mathbb{N}$. Thus, we know that the assumption $P(\gamma < \lambda) \not\Rightarrow P(\lambda)$ is false.

Then $P(\gamma < \lambda) \Rightarrow P(\lambda)$ is true, i.e., the **Limit Case** is true.

That completes the proof of Lemma 5. $\square$

Additionally, we also need the following results on properties of zeros of entire function for understanding the multiplicity of zeros of $\xi(s)$.

Lemma 6. *Let $f(s)$ be a non-zero entire function, and let s_0 be a zero of $f(s)$. Then the multiplicity of s_0 is a finite positive integer.*

Proof. Let $f(s) \not\equiv 0, s \in \mathbb{C}$, be an entire function, which means it is holomorphic on the whole complex plane. Suppose $f(s)$ has a zero at $s_0 \in \mathbb{C}$ of multiplicity m , then $f(s) = (s - s_0)^m g(s)$, where $g(s)$ is also an entire function and $g(s_0) \neq 0$.

Assume for contradiction that m is infinite, which implies there exists an accumulation point of zeros in the neighbor of s_0 . Then, by Identity Theorem for holomorphic functions, and considering "0" is also an entire function, we have $f(s) \equiv 0, s \in \mathbb{C}$, which contradicts the given condition that $f(s) \not\equiv 0, s \in \mathbb{C}$. Thus, the assumption is false, i.e., m must be a finite positive integer.

That completes the proof of Lemma 6. $\square$

Remark 2. *Statements similar to Lemma 6 can be found in Reference [30] and other related textbooks/monographs.*

Lemma 7. *Let $f(s)$ be a non-zero entire function, and let s_0 be a zero of $f(s)$. Then the multiplicity of s_0 is unique.*

Proof. Let $f(s) \not\equiv 0, s \in \mathbb{C}$, be an entire function, which has a multiple zero at $s_0 \in \mathbb{C}$ of multiplicity m . We can write: $f(s) = (s - s_0)^m g(s)$, where $g(s)$ is also an entire function and $g(s_0) \neq 0$.

Assume for contradiction that there exists another integer $n \neq m$ such that n is also a multiplicity of the zero s_0 . This means we can also write: $f(s) = (s - s_0)^n h(s)$, where $h(s)$ is an entire function and $h(s_0) \neq 0$.

Since both expressions for $f(s)$ must be equal, we then obtain $(s - s_0)^m g(s) = (s - s_0)^n h(s)$. Without loss of generality, consider $m > n$, then we have: $(s - s_0)^{m-n} g(s) = h(s) \Rightarrow h(s_0) = 0$, which is a contradiction to $h(s_0) \neq 0$. Thus, the assumption is false, i.e., the multiplicity of a zero of any non-zero entire function is unique.

That completes the proof of Lemma 7. $\square$

3. Key Lemma

In this section, we prove the key lemma - Lemma 8, which is substantial for the proof of the RH.

Lemma 8. *Given two entire functions represented as absolutely convergent (on the whole complex plane) infinite products of polynomial factors*

$$f(s) = \prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \quad (11)$$

and

$$f(1-s) = \prod_{i=1}^{\infty} \left(1 + \frac{(1-s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \quad (12)$$

where s is the complex variable, $\rho_i = \alpha_i + j\beta_i$ and $\bar{\rho}_i = \alpha_i - j\beta_i$ are the complex conjugate zeros of the completed zeta function $\zeta(s)$, $0 < \alpha_i < 1$ and $\beta_i \neq 0$ are real numbers, $0 < |\beta_1| \leq |\beta_2| \leq |\beta_3| \leq \dots$, $m_i \geq 1$ is the multiplicity of quadruplets of zeros $(\rho_i, \bar{\rho}_i, 1 - \rho_i, 1 - \bar{\rho}_i)$.

Then we have

$$f(s) = f(1-s) \Leftrightarrow \begin{cases} \alpha_i = \frac{1}{2} \\ 0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots \\ i = 1, 2, 3, \dots \end{cases} \quad (13)$$

Remark 3. As stated in the Abstract, the divisibility contained in the equation $f(s) = f(1-s)$ and the uniqueness of m_i are the key points to the proof of Lemma 8, as they ensure that each polynomial factor can only divide (and thereby equal) the corresponding factor on the opposite side of the equation; otherwise, it would violate the uniqueness of m_i . As stated in Lemma 6 and Lemma 7, m_i is finite and unique, and then unchangeable.

Proof. First of all, we have the following fact about a special second-order polynomial (in the variable s) equation

$$(s - \alpha)^2 = (1 - s - \alpha)^2 \Leftrightarrow \alpha = \frac{1}{2} \quad (\alpha \in \mathbb{R}) \quad (14)$$

It is obvious that

$$\begin{aligned} f(s) = f(1-s) &\Leftrightarrow \prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} = \prod_{i=1}^{\infty} \left(1 + \frac{(1-s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \\ &\Leftrightarrow (\text{by rearrangement of absolutely convergent infinite products of both sides}) \quad (15) \\ \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) &= \left(1 + \frac{(1-s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1-s) \end{aligned}$$

where

$$f_l(s) = \prod_{i \in \mathbb{I} \setminus \{l\}} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \quad (16)$$

$$f_l(1-s) = \prod_{i \in \mathbb{I} \setminus \{l\}} \left(1 + \frac{(1-s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \quad (17)$$

with $\mathbb{I} = \{1, 2, 3, \dots\}$, and " l " is an arbitrary element of set $\mathbb{I}$. In brief, $i \in \mathbb{I} \setminus \{l\}$ means that i runs over the elements of $\mathbb{I}$ excluding " l ".

Then we have

$$\begin{aligned}
 \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) &= \left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1 - s) \\
 &\Rightarrow (\text{according to the definition of divisibility of infinite products of polynomial factors}) \\
 &\left\{ \begin{array}{l} \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} \Big| \left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1 - s) \\ \left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} \Big| \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) \end{array} \right. \quad (18) \\
 &\Rightarrow (\text{according to the transitive property of divisibility}) \\
 &\left\{ \begin{array}{l} \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1 - s) \\ \left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) \end{array} \right.
 \end{aligned}$$

Next, we exclude the possibility of $\left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right) \Big| f_l(1 - s)$ and $\left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right) \Big| f_l(s)$. Considering the polynomial factor $\left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right)$, $0 < \alpha_l < 1$, $\beta_l \neq 0$, with discriminant $\Delta = \left(\frac{2\alpha_l}{\beta_l^2}\right)^2 - 4 \cdot \frac{1}{\beta_l^2} \left(1 + \frac{\alpha_l^2}{\beta_l^2}\right) = -4 \cdot \frac{1}{\beta_l^2} < 0$, is irreducible over the field $\mathbb{R}$, similarly, $\left(1 + \frac{(1 - s - \alpha_l)^2}{\beta_l^2}\right)$ with discriminant $\Delta = -4 \cdot \frac{1}{\beta_l^2} < 0$ is also irreducible over the field $\mathbb{R}$, we know that

$$\begin{aligned}
 &\left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right) \Big| f_l(1 - s) \\
 &\Rightarrow (\text{by Lemma 5}) \\
 &\left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i}, i \neq l \\
 &\Rightarrow (\text{by Lemma 3}) \\
 &\left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right), i \neq l \\
 &\Rightarrow (\text{the dividend polynomial and the divisor polynomial are of the same degree}) \\
 &\left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right) = k \left(1 + \frac{(s - \alpha_l)^2}{\beta_l^2}\right), i \neq l, k \in \mathbb{R}, k \neq 0 \\
 &\Rightarrow (\text{by comparing the like terms in the above polynomial equation}) \\
 &\left\{ \begin{array}{l} \frac{1}{\beta_i^2} = k \cdot \frac{1}{\beta_l^2} \\ \frac{2(1 - \alpha_i)}{\beta_i^2} = k \cdot \frac{2\alpha_l}{\beta_l^2} \\ 1 + \frac{(1 - \alpha_i)^2}{\beta_i^2} = k \left(1 + \frac{\alpha_l^2}{\beta_l^2}\right) \end{array} \right. \\
 &\Rightarrow \\
 &\alpha_i + \alpha_l = 1, \beta_i^2 = \beta_l^2, k = 1, i \neq l
 \end{aligned}$$

and similarly

$$\begin{aligned}
& \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \Big| f_l(s) \\
& \Rightarrow (\text{by Lemma 5}) \\
& \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(s-\alpha_i)^2}{\beta_i^2}\right)^{m_i}, i \neq l \\
& \Rightarrow (\text{by Lemma 3}) \\
& \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \Big| \left(1 + \frac{(s-\alpha_i)^2}{\beta_i^2}\right), i \neq l \\
& \Rightarrow (\text{the dividend polynomial and the divisor polynomial are of the same degree}) \\
& \left(1 + \frac{(s-\alpha_i)^2}{\beta_i^2}\right) = k \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right), i \neq l, k \in \mathbb{R}, k \neq 0 \\
& \Rightarrow (\text{by comparing the like terms in the above polynomial equation}) \\
& \alpha_i + \alpha_l = 1, \beta_i^2 = \beta_l^2, k = 1, i \neq l
\end{aligned}$$

It should be noted that $\alpha_i + \alpha_l = 1, \beta_i^2 = \beta_l^2, i \neq l$ imply $(\rho_i, \bar{\rho}_i, 1 - \rho_i, 1 - \bar{\rho}_i)$ and $(\rho_l, \bar{\rho}_l, 1 - \rho_l, 1 - \bar{\rho}_l)$ are the same zeros in terms of quadruplets, which contradicts the uniqueness of the multiplicity of zeros of $\zeta(s)$.

Thus, in order to keep the multiplicities of zeros of $\zeta(s)$ unchanged, $\left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right)$ can not divide $f_l(1-s)$, $\left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right)$ can not divide $f_l(s)$, denoted as $\left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \nmid f_l(1-s)$, $\left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \nmid f_l(s)$, respectively. Therefore, we obtain from Eq.(18) the following result.

$$\begin{aligned}
& \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) = \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1-s) \\
& \Rightarrow \\
& \left\{ \begin{array}{l} \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(1-s) \\ \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} f_l(s) \end{array} \right. \\
& \Rightarrow (\text{by Lemma 5 and the fact } \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \nmid f_l(1-s), \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \nmid f_l(s)) \\
& \left\{ \begin{array}{l} \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} \\ \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right)^{m_l} \end{array} \right. \tag{19} \\
& \Rightarrow (\text{by Lemma 3}) \\
& \left\{ \begin{array}{l} \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \\ \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right) \mid \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) \end{array} \right. \\
& \Rightarrow \left(1 + \frac{(s-\alpha_l)^2}{\beta_l^2}\right) = k \left(1 + \frac{(1-s-\alpha_l)^2}{\beta_l^2}\right), k \in \mathbb{R}, k \neq 0 \\
& \Rightarrow (\text{by comparing the like terms in the above polynomial equation}) \\
& k = 1, \alpha_l = \frac{1}{2}
\end{aligned}$$

Let $l = 1, 2, 3, \dots$, and repeat the above process as shown in Eq.(19), we get

$$\begin{aligned}
\prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} &= \prod_{i=1}^{\infty} \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \\
&\Rightarrow \\
\left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right) &= \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right) \\
&\Rightarrow \\
\alpha_i &= \frac{1}{2}, i = 1, 2, 3, \dots
\end{aligned} \tag{20}$$

On the other hand, based on Eq.(14), we have the following fact

$$\begin{aligned}
\alpha_i &= \frac{1}{2}, i = 1, 2, 3, \dots \\
&\Rightarrow \text{(according to Eq.(14))} \\
(s - \alpha_i)^2 &= (1 - s - \alpha_i)^2 \\
&\Rightarrow \text{(considering } \beta_i \neq 0) \\
\left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right) &= \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right) \\
&\Rightarrow \text{(considering } m_i \geq 1) \\
\left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} &= \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \\
&\Rightarrow \text{(taking infinite product of the above equations with absolute convergence given in Lemma 8)} \\
\prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} &= \prod_{i=1}^{\infty} \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i}
\end{aligned} \tag{21}$$

In addition, limiting the imaginary parts β_i of zeros to $0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots$ in order to keep the multiplicities of zeros unchanged while $\alpha_i = \frac{1}{2}$, we finally get

$$\begin{aligned}
\prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} &= \prod_{i=1}^{\infty} \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \\
&\Leftrightarrow \\
&\left\{ \begin{array}{l} \alpha_i = \frac{1}{2} \\ 0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots \\ i = 1, 2, 3, \dots \end{array} \right.
\end{aligned}$$

i.e.,

$$f(s) = f(1 - s) \Leftrightarrow \left\{ \begin{array}{l} \alpha_i = \frac{1}{2} \\ 0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots \\ i = 1, 2, 3, \dots \end{array} \right.$$

That completes the proof of Lemma 8. $\square$

4. A Proof of the RH

This section presents a proof of the Riemann Hypothesis. We first prove that Statement 2 of the RH is true, and then by Lemma 2, Statement 1 of the RH is also true. To be brief, to prove the Riemann

Hypothesis, it suffices to show that $\alpha_i = \frac{1}{2}, i = 1, 2, 3, \dots$ in the new expression of $\zeta(s)$ as shown in Eq.(25).

Proof of the RH. The details are delivered in three steps as follows.

Step 1:

It is well-known that zeros of $\zeta(s)$ always come in complex conjugate pairs. Then by pairing $\rho_i = \alpha_i + j\beta_i$ and $\bar{\rho}_i = \alpha_i - j\beta_i$ in the Hadamard product as shown in Eq.(10), we have

$$\begin{aligned}\zeta(s) &= \zeta(0) \prod_{\rho} \left(1 - \frac{s}{\rho}\right) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{s}{\rho_i}\right) \left(1 - \frac{s}{\bar{\rho}_i}\right) \\ &= \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{s}{\alpha_i + j\beta_i}\right) \left(1 - \frac{s}{\alpha_i - j\beta_i}\right) = \zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)\end{aligned}\quad (22)$$

where $0 < \alpha_i < 1, \beta_i \neq 0$ (according to Lemma 1).

The absolute convergence of the infinite product in Eq.(22) in the form

$$\zeta(s) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{s}{\rho_i}\right) \left(1 - \frac{s}{\bar{\rho}_i}\right) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{s(2\alpha_i - s)}{|\rho_i|^2}\right) \quad (23)$$

depends on the convergence of infinite series $\sum_{i=1}^{\infty} \frac{1}{|\rho_i|^2}$ (since $|s| < \infty \Rightarrow |s(2\alpha_i - s)| < \infty$), which is an obvious fact according to Theorem 2 in Section 2, Chapter IV of Ref.[11]. Thus, the infinite products as shown in Eq.(23) and Eq.(22) are absolutely convergent for $|s| < \infty$.

Further, considering the absolute convergence of

$$\zeta(s) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{s(2\alpha_i - s)}{|\rho_i|^2}\right) = \zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right) \quad (24)$$

we have the following new expression of $\zeta(s)$ by putting all the possible multiple factors (zeros) together:

$$\zeta(s) = \zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)^{m_i} \quad (25)$$

where $m_i \geq 1$ is the multiplicity of $\rho_i / \bar{\rho}_i, i = 1, 2, 3, \dots$.

Step 2: Replacing s with $1 - s$ in Eq.(25), we obtain the infinite product expression of $\zeta(1 - s)$, i.e.,

$$\zeta(1 - s) = \zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(1 - s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)^{m_i} \quad (26)$$

where $m_i \geq 1$ is the multiplicity of $1 - \rho_i / 1 - \bar{\rho}_i, i = 1, 2, 3, \dots$.

The absolute convergence of the infinite product as shown in Eq.(26) can be reduced to that of $\zeta(1 - s) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{1-s}{\rho_i}\right) \left(1 - \frac{1-s}{\bar{\rho}_i}\right) = \zeta(0) \prod_{i=1}^{\infty} \left(1 - \frac{(1-s)(2\alpha_i - 1 + s)}{|\rho_i|^2}\right)$, whose absolute convergence depends also on the convergence of infinite series $\sum_{i=1}^{\infty} \frac{1}{|\rho_i|^2}$ (since $|s| < \infty \Rightarrow |(1-s)(2\alpha_i - 1 + s)| < \infty$). Then from the analysis in Step 1, the infinite product as shown in Eq.(26) is absolutely convergent for $|s| < \infty$.

Step 3: According to the functional equation $\zeta(s) = \zeta(1 - s)$, and considering Eq.(25) and Eq.(26), we have

$$\zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)^{m_i} = \zeta(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(1 - s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2}\right)^{m_i} \quad (27)$$

which is equivalent to

$$\prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} = \prod_{i=1}^{\infty} \left(1 + \frac{(1 - s - \alpha_i)^2}{\beta_i^2}\right)^{m_i} \quad (28)$$

where $m_i \geq 1$ is the multiplicity of quadruplets $(\rho_i, \bar{\rho}_i, 1 - \rho_i, 1 - \bar{\rho}_i)$, $i = 1, 2, 3, \dots$, β_i are in order of increasing $|\beta_i|$, i.e., $0 < |\beta_1| \leq |\beta_2| \leq |\beta_3| \leq \dots$.

To check the absolute convergence (on the whole complex plane) of both sides of Eq.(28), it suffices to prove the convergence of infinite series $\sum_{i=1}^{\infty} \frac{1}{\beta_i^2}$, which is an obvious fact because

$$0 < \alpha_i < 1, |\rho_i|^2 \rightarrow \infty \text{ (since } \sum_{i=1}^{\infty} \frac{1}{|\rho_i|^2} \text{ is convergent, then } \frac{1}{|\rho_i|^2} \rightarrow 0) \Rightarrow |\beta_i|^2 \rightarrow \infty.$$

Then we have $\lim_{i \rightarrow \infty} \frac{\beta_i^2}{|\rho_i|^2} = \lim_{i \rightarrow \infty} \frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} = 1$, that means $\sum_{i=1}^{\infty} \frac{1}{\beta_i^2}$ and $\sum_{i=1}^{\infty} \frac{1}{|\rho_i|^2}$ have the same convergence. Furthermore, both sides of Eq.(28) converge to entire functions, because they differ with the entire function $\xi(s)$ by a non-zero multiplicative constant, i.e.,

$$\begin{aligned} \xi(s) &= \xi(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} + \frac{(s - \alpha_i)^2}{\alpha_i^2 + \beta_i^2} \right)^{m_i} \\ &= \xi(0) \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} \right)^{m_i} \prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2} \right)^{m_i} \\ &= c \cdot \prod_{i=1}^{\infty} \left(1 + \frac{(s - \alpha_i)^2}{\beta_i^2} \right)^{m_i} \end{aligned} \quad (29)$$

where c is a non-zero constant, see Lemma 9 for details.

Finally, according to Lemma 8, Eq.(28) is equivalent to

$$\alpha_i = \frac{1}{2}; 0 < |\beta_1| < |\beta_2| < |\beta_3| < \dots; i = 1, 2, 3, \dots \quad (30)$$

Thus, we conclude that all zeros of the completed zeta function $\xi(s)$ have real part equal to $\frac{1}{2}$, i.e., Statement 2 of the RH is true. According to Lemma 2, Statement 1 of the RH is also true, i.e., all the non-trivial zeros of the Riemann zeta function $\zeta(s)$ have real part equal to $\frac{1}{2}$.

That completes the proof of the RH. $\square$

Lemma 9. The infinite product $\prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} \right)^{m_i}$ converges to a non-zero constant, given the conditions: $0 < \alpha_i < 1, \beta_i \neq 0, \sum_{i=1}^{\infty} \frac{1}{\beta_i^2} < \infty$, and $m_i \geq 1$ is the multiplicity of zero $\alpha_i + j\beta_i$.

Proof. First of all, we know that

$$\prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} \right)^{m_i} = \prod_{i=1}^{\infty} \frac{\beta_i^2}{\alpha_i^2 + \beta_i^2}$$

in the right side expression, i^{th} factor appears m_i times.

Let $a_i = \frac{\alpha_i^2}{\alpha_i^2 + \beta_i^2}$, then $\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} = 1 - \frac{\alpha_i^2}{\alpha_i^2 + \beta_i^2} = 1 - a_i$.

Since $0 < \alpha_i < 1$ and $\beta_i \neq 0$, we have: $0 < a_i < \frac{1}{\beta_i^2}$. Then $\sum_{i=1}^{\infty} \frac{1}{\beta_i^2} < \infty$ (given condition) implies $\sum_{i=1}^{\infty} |a_i| = \sum_{i=1}^{\infty} a_i < \infty$ (absolute convergence).

Further, the absolute convergence of $\sum_{i=1}^{\infty} a_i$ guarantees that the product $\prod_{i=1}^{\infty} (1 - a_i) = \prod_{i=1}^{\infty} \frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} = \prod_{i=1}^{\infty} \left(\frac{\beta_i^2}{\alpha_i^2 + \beta_i^2} \right)^{m_i}$ converges to a non-zero constant.

That completes the proof of Lemma 9. $\square$

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