

Precision Design and Fabrication of Noise-free High-Frequency Amplifier Board for Enhanced Signal Processing

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Abstract. An optical signal processing system is widely used for long-distance signal transmission with high speed and low attenuation. It plays a fundamental role in optical communication systems that involves transmitting, receiving, amplifying, and manipulating optical signals which are high-frequency signals. This paper portrays the design of a high-frequency amplifier to amplify the low-amplitude high-frequency, electrical signal procured from the optical signal. A four-stage high frequency amplifier has been designed using an AD8009 high-frequency Op-amp for the highest frequency of 1GHz, and for the fastest rise time of 0.35 nanoseconds. This amplifier board incorporates the high-frequency PCB design rules related to the characteristic impedance, impedance matching, signal crosstalk, the propagation delay of the transmission lines, transmission techniques for the ground plane, and termination of transmission lines for the effective use of high-frequency signals. It has also counted on the issues of electromagnetic interference, power supply decoupling, noise, and high-speed operational amplifier. The proposed system resulted in suitable amplification of low amplitude high-frequency electrical signal, having no signal cross-talks, electromagnetic interference, signal ringing, signal reflections, and posed larger bandwidth. The improved quality of high frequency processed signals with good signal integrity and moderate circuit oscillations achieved by this system will benefit the optical communication system.

Keywords— High-frequency, Optical Signal Processing, Signal integrity, Characteristics impedance, High- frequency amplifier, Impedance matching

1 Introduction

High frequency refers to a range of frequencies higher than what is commonly used for everyday communications or power transmission. Generally, it refers to frequencies in range of several megahertz to gigahertz. In terms of electromagnetic waves, the high frequency falls in the upper part of the electromagnetic spectrum, which ranges from extremely low frequencies to gamma rays. As defined by the International Telecommunication Union, the high frequency operates in the range of three to thirty megahertz, and its wavelengths extend from ten to one hundred meters. The frequency immediately below the high frequency is called the medium frequency and ranges from 300kHz to 3MHz, while the band next to the high frequency is called the very high frequency and ranges from 30MHz to 300MHz. In practical applications, the high frequency is associated with technologies and systems that operate at

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higher speeds, higher data rates, and shorter wavelengths. Thus, it is used in amateur radio, military and government communications, radar communications, and international and regional short-wave broadcasting. This frequency is very popular in optical signal processing systems, where the photo diode converts the optical signal from the light source into an electrical current signal. A transimpedance amplifier converts this current signal into a small amplitude voltage signal and then a high frequency amplifier amplifies it.

For the efficient use of the high frequency signals, analog processing is implemented. Indeed, when performing analog signal processing, several issues can arise. These design issues are power supply decoupling, the high frequency effect in resistors, capacitors, inductors, electromagnetic interference issues, crosstalk problems, design complications of high frequency PCB design, high-speed opamps, problems in PCB tracks, skin effect, etc. and noise problem too. This results in the loss of signal integrity, ringing effect, reduction in bandwidth, opamp oscillations, circuit resonance and oscillations, electromagnetic interference, cross-talks, signal reflections, etc. that affect the output.

This paper describes the design of a high frequency amplifier that amplifies the low amplitude, high frequency electrical signal; by considering all the design rules of high frequency. The system was designed considering the design rules related to the characteristic impedance, impedance matching, signal crosstalk, the propagation delay of the transmission lines, transmission techniques for the ground plane, and termination of transmission lines. For the low insertion loss, low reflection coefficient, and high reliability, the model also made use of a specific type of high-frequency connector called Sub Miniature version A (SMA) edge connector. The combined effect of improved signal quality, good signal integrity, reduced circuit oscillations, and maximum closed-loop bandwidth by this system makes this system effective in high-frequency applications such as optical communication systems.

2 System Description:

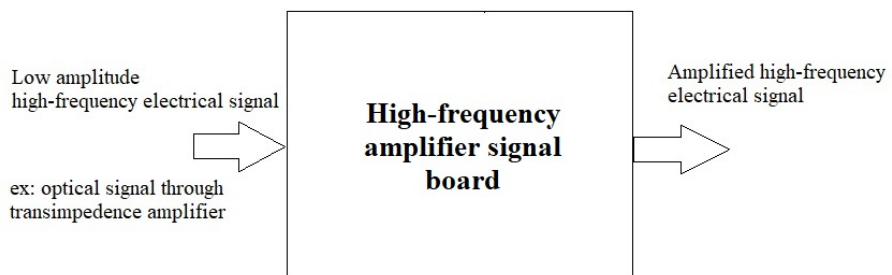


Figure 1: Proposed System Diagram

Figure 1 above shows the proposed system diagram designed for effective use of high frequency signals. It obtains the low amplitude high frequency electrical signal from the optical signal through a trans-impedance amplifier and output the amplified high frequency electrical signal.

Routing techniques, impedance matching concepts, transmission line termination techniques, treatment of characteristic impedance, and transmission line propagation delay were implemented. Also,

micro-strip transmission techniques and power supply decoupling method were used to achieve better quality of processed high frequency signal.

The system employs a four-stage high-frequency amplifier with an AD8009 high-frequency operational amplifier. The AD8009 is an ultrahigh-speed current feedback amplifier having a slew rate of 5500 V/s and a rise time of 545 picoseconds, making it ideal as a pulse amplifier. Its high slew rate reduces the effect of slew rate limiting and results in the large signal bandwidth of 440 MHz. The AD8009 can deliver over 175 mA of load current and is available in a small SOIC package.

Before fabricating the board of the four-stage high-frequency amplifier, the simulation of this amplifier was performed using Multisim V14.0 software from National Instrument. Figure 2 below shows the Multisim workspace for the four-stage high-frequency amplifier, each amplifier designed with a gain of two.

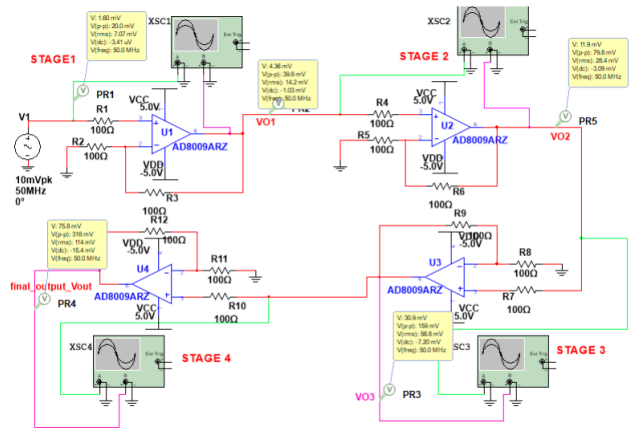
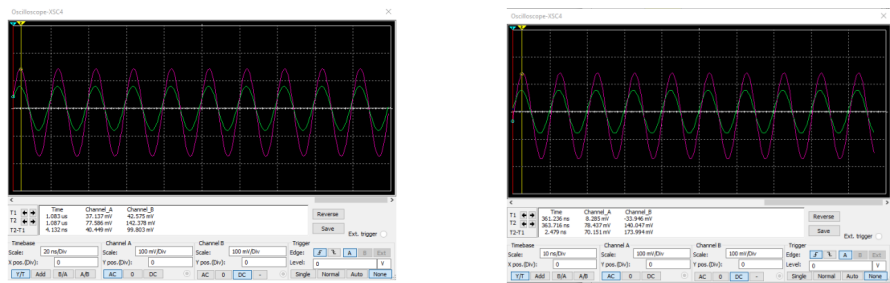


Figure 2: Multisim workspace for the AD8009 four-stage high-frequency amplifier

Figure 3 below present some of the simulation results for various frequencies. Figure 3a shows the simulation results for fourth stage output of high-frequency amplifier at 50MHz and figure 3b presents the fourth stage output of the high-frequency amplifier at 100MHz,



(a) Simulation results for fourth stage output of high-frequency amplifier at 50MHz

(b) Simulation results for fourth stage output of high-frequency amplifier at 100MHz

Figure 3: Simulation results for fourth stage output of high-frequency amplifier

Once the desired simulation results were obtained, the design of the four-stage high-frequency amplifier board was implemented using Autodesk EAGLE V8.5.1 software. The board was designed

using the AD8009 low-distortion high-frequency operational amplifier for the highest frequency of 1 GHz with a rise time of 0.35 nanoseconds. Some PCB considerations were made, such as the input to the sink (high frequency amplifier board) being a millivolt test signal from the function generator and the output being a voltage signal. The power supply used was an opamp's dual power supply and a function generator as a test input supply.

All PCB design rules for high frequency signals were considered. To improve the signal integrity of the design, a double-layer PCB was used to separate ground and power planes. This involved routing the high-frequency signals on separate layers, which minimized cross interference between the signals. Mutual interference was minimized by avoiding the routing of parallel traces and when parallel traces were used, the distance between them was considered as three times the trace width [1]. For the wide frequency range, the layout provided a micro-strip transmission technique where the high frequency signal flowed in the trace across the ground plane [2].

To ensure reliable signal transmission and minimize signal distortion, controlled impedance lines were considered. For this purpose, the critical length of transmission lines was calculated [3]. After calculating the critical length, depending on the transmission line length, two cases were considered for the application of controlled impedance line [2]. For the PCB developed, the line length varied depending on the connection on the board workspace. Therefore, the requirements for a controlled impedance line also changed. On the designed PCB, wherever the controlled impedance lines were used, the characteristic impedance of 50ohms was implemented [2],[4] . This characteristic impedance was determined using the online impedance calculator. Figure 4 shows the online characteristics impedance calculator, which determined the characteristic impedance of the transmission line as 50ohms.

Figure 4: Online characteristics impedance calculator

According to the above calculations, a trace width of 18 mils was used in this scheme to maintain the characteristic impedance of 50ohms for the controlled impedance line. This assured the impedance matching in the design that reduced the signal reflections and hence the ringing effect.

To avoid the ringing effect, the system was provided with a termination of the transmission line, for which the propagation delay of the transmission line was mathematically calculated as follows [2]

$$tpd_{in}^{ps} = 85 * \sqrt{0.475\epsilon_r + 0.67} \quad (1)$$

where,
 ϵ_r = PCB dielectric constant

After determining the propagation delay, the termination of the transmission lines was determined according to the two-inch/nanosecond rule [2].

$$Propagationdelayofthetrack \geq \frac{1}{2} * [(Tr)or(Tf)] \tag{2}$$

Where,
Tr= rise time of the signal= 0.35ns
Tf= fall time of the signal

As per calculation of propagation delay and the two-inch/nanosecond rule, the calculated propagation delay of this PCB layout was less than half of the rise time of the signal; therefore, the termination of the transmission line was not implemented in its characteristic impedance for this design [2].

To obtain the minimum trace width, an online trace width calculator was used for this model, which was designed to handle 1 A of current. Figure 5 shown below is the online trace width calculator used to calculate the trace width for 1A PCB.

This Javascript web calculator calculates the trace width for printed circuit board conductors for a given current using formulas from IPC-2221 (formerly IPC-D-275).

Inputs:

Current	1	Amps
Thickness	1	oz/ft ² ▾

Optional Inputs:

Temperature Rise	10	Deg C ▾
Ambient Temperature	25	Deg C ▾
Trace Length	1181	mil ▾

Results for Internal Layers:

Required Trace Width	30.8	mil ▾
Resistance	0.0194	Ohms
Voltage Drop	0.0194	Volts
Power Loss	0.0194	Watts

Results for External Layers in Air:

Required Trace Width	11.8	mil ▾
Resistance	0.0504	Ohms
Voltage Drop	0.0504	Volts
Power Loss	0.0504	Watts

Figure 5: Online trace width calculator

Based on the above calculations, the minimum trace width of the traces used for this layout was 11.8 mils, which is approximately 12 mils. The traces in the designed layout with a minimum trace width of 12 mils carried 1A current with good signal integrity.

To further improve the signal integrity and signal timing, matched lengths of transmission lines were used on the designed high frequency PCB. For length matching, delays were added to the traces in Autodesk EAGLE V8.5.1 software using the meander tool. The length-matched transmission lines in the design were the traces from the decoupling capacitor to the power supply pins of the opamp. Because of the length matching, all four opamps used in this design received +/-5 V supply at the same time, even though all the opamps used a single dual power supply.

The scientific estimates of the maximum PCB track length decided the track as a transmission line or as a trace. For this purpose, the maximum PCB track length was mathematically calculated using the following formula [5],[6].

$$MaximumPCBtracklength = Tr * 2inch/ns \tag{3}$$

Where,
Tr = rise time of input signal

In this layout, the track with a length equal to or greater than the calculated maximum PCB track length was considered as a transmission line, and the track with a length less than the calculated maximum PCB track length was considered as a trace [5],[6]. The designed PCB was carefully examined

for stray capacitance, skin effect and skin resistance. The mathematical calculation of stray capacitance for this layout is [2].

$$C_{stray} = \frac{0.00885 * \epsilon_r * A}{d} pF \quad (4)$$

Where,

ϵ_r = dielectric constant of the board material

d = board thickness

A = area of the board

Depending on the minimum and maximum thickness of the designed PCB, the minimum and maximum stray capacitance was obtained from the above calculation. According to the calculation, the designed high frequency PCB has a stray capacitance of about 0.2nF - 2.59nF, which does not affect the performance of the circuit. The capacitance of the trace across the ground plane in this design was about 2.8pf/cm² [2], which ensures the reliable operation of the circuit and maintains signal integrity.

Since the PCB is a high frequency PCB, the skin effect of the PCB was considered, and the skin depth was calculated methodically by [2].

$$skindepth(\delta) = \frac{6.61}{\sqrt{f}} \quad (5)$$

Where,

f = frequency of the applied signal

For this high frequency amplifier board, the calculated skin depth was 2.09 μm . Thus, at a distance of 2.09 μm from the surface of the conductor, the current density drops to about 37% of its value at the surface.

Skin resistance is the most important result of the skin effect on the impedance of the transmission line, the value of which was taken into account in the design of the printed circuit board. Mathematically, the value of skin resistance was calculated by [6].

$$skinresistance = 2.6 * 10^{-7} \sqrt{f} \quad (6)$$

where,

f = applied input frequency

For this PCB, the calculated value of skin resistance was 8.22 p Ω /sq. which triggers the skin effect.

The characteristic capacitance of a transmission line is of great importance because it affects impedance matching, signal propagation, signal delay, crosstalk, signal integrity, and design considerations. The characteristic capacitance of the transmission line for this design was analytically calculated by [5],[6].

$$Co(pF/inch) = \frac{0.67(\epsilon_r + 1.41)}{\ln\left[\frac{5.98H}{(0.8W+T)}\right]} \quad (7)$$

Where,

ϵ_r = dielectric constant

H = dielectric thickness

W = width of conductor

T = Thickness of trace

The mathematically calculated value of the characteristic capacitance for this high-frequency amplifier board was 2.729pF/inch, which resulted in efficient signal transmission and reliable performance.

To avoid the noise in the power supply, the power supply decoupling method was used. In this system, a bypass electrolytic capacitor of 10 μ f was connected in parallel with a ceramic capacitor of 0.1 μ f

between the supply pin and ground. These bypass capacitors decoupled the current loop for transients into smaller loops and prevented noise on the power supply lines [7]. They provided a switching current without drop [7].

The footprint of IC AD8009 was created in EAGLE by following three steps - package creation, symbol creation, and device creation. Besides, the Autodesk EAGLE software modified the opamp's IC socket. For reliable connectivity, the proto-type used a particular type of high-frequency connector called an SMA (Sub Miniature A) edge connector.

Figure 6 below shows the designed and fabricated PCB board

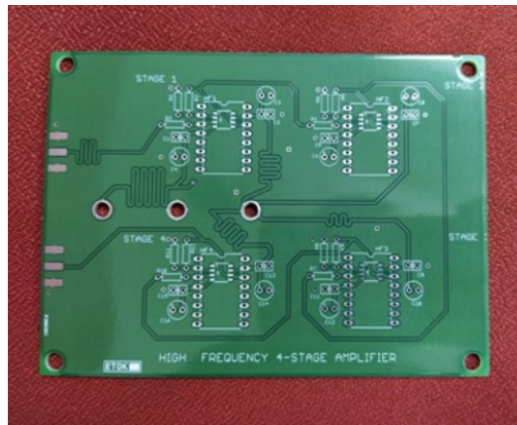


Figure 6: High frequency four-stage amplifier board

3 Results

The four-stage high frequency amplifier board was structured for an overall gain of ten thousand, having an individual stage gain of ten. Each stage of the high-frequency amplifier was tested discretely. Figure 7 illustrates the fabricated high-frequency four-stage amplifier board with its assembled components for board testing.

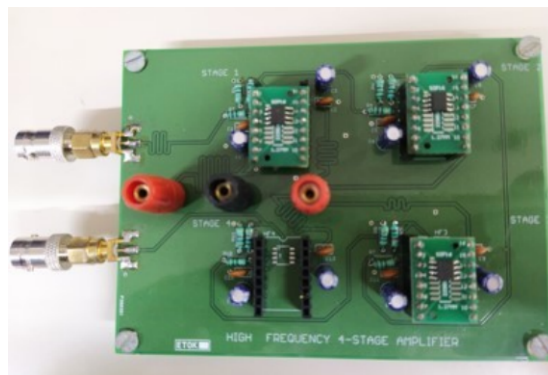


Figure 7: High frequency four-stage amplifier board testing

Stage one of the four-stage high frequency amplifier was tested for the distinct input frequencies. It was observed that the output of the stage one amplifier was ten times the input voltage. This stage

achieved the amplification with the gain of ten without any noise, cross-talks, and better signal reliability. Figure 8 shows the input and output waveform of stage-one high-frequency amplifier at 10MHz.

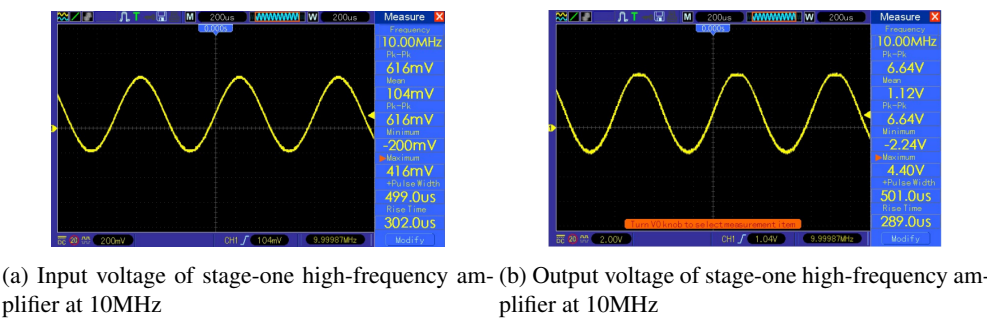


Figure 8: Input and Output waveform of stage-one high-frequency amplifier at 10MHz

However, through the individual testing of the second-stage high frequency amplifier, more signal distortions were experienced, due to the direct implementation of the input to this stage. Hence, the first and second stages of the high frequency amplifier were tested in cascade mode. In cascade mode, it was found that there was no signal disturbance in the output stage. The input value was selected suitably by trial-and-error methods so that the op-amp does not go under saturation.

Similarly, figure 9 below shows the input and output waveform of stage-two high-frequency amplifier at 10MHz.

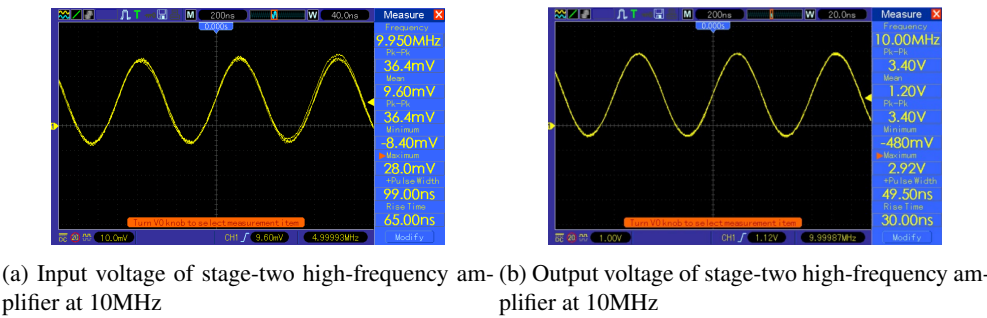


Figure 9: Input and Output waveform of stage-two high-frequency amplifier at 10MHz

Considering observations, each stage worked satisfactorily with the gain ten and gave noiseless output having no cross-talks, EMI, signal ringing, and reflections as illustrated in figure8b and 9b.

As the gain increased to thousand, the input value in the range of microvolt was selected to obtain satisfactorily output. This stage was tested in cascade mode with varied frequencies of microvolt input. Unfortunately, the function generator above 50MHz (gigahertz) range was not available so the testing of the three stage high frequency amplifier was carried out up to 50MHz. The table below displays the observations made for the three-stage high-frequency amplifier.

It was observed that the stage three high-frequency amplifier gave the satisfactorily amplified output having gain thousand. The amplified output signal thus achieved was noise-free and had good signal integrity.

Table 1: Three-stage amplifier

OBSERVATION TABLE: THREE-STAGE HIGH-FREQUENCY AMPLIFIER										
Opamp AD8009 Non-inverting configuration (Gain = 10/stage)										
Sr. No.	Frequency (Hz)	Stage1		Stage 2		Stage 3		Gain		
		Vin1 (mV)	Vo1 (mV)	Vin2 (mV)	Vo2 (mV)	Vin3 (mV)	Vo3 (V)	G1	G2	G3
1.	1k	3	38	37	316	320	3	12.66	8.5	9.375
2.	50k	3	38.4	39.2	376	376	3.8	12.66	9.59	10.1
3.	100k	3	35.2	35.2	380	400	3.9	11.7	11.08	9.75
4.	500k	3	32	32	336	368	3.2	10.66	10.5	8.69
5.	1M	3	38	39	368	368	3.6	12.66	9.4	9.7
6.	2M	3	30	32	368	368	3.6	10	11.5	9.7
7.	3M	3	32	33.6	392	370	3.4	10.66	11.6	9.04
8.	4M	3	34	30	336	352	3.3	11.33	9.3	9.375
9..	5M	3	35	36	348	356	3.2	9.66	9.6	8.98
10.	10M	3	36	39	364	368	3.1	12	9.3	8.42

Since the stage four amplifier gave an overall gain of ten thousand, it was difficult to protect the opamps from undergoing saturation as nano-volt signals from a function generator were not possible to obtain. Thus, the stage-four testing was avoided, but it could be implemented if input signal amplitude varies in the picovolt to nanovolt range.

The four-stage high-frequency amplifier using AD8009 high-frequency opamp can work satisfactorily with no signal crosstalk, noise, electromagnetic interference, and good signal integrity up to 320MHz with a gain of ten.

4 Conclusion

Signal integrity, characteristics impedance, critical length, and controlled impedance of the transmission lines are crucial factors to consider when designing a high frequency amplifier. The other critical parameters, such as the electromagnetic interference, signal cross-talks, power-supply decoupling, opamp stability, and grounding, should also be treated while constructing the high-frequency amplifier. The results indicate that the designed four-stage HF amplifier gave suitable amplification of low amplitude high-frequency electrical signal. The amplified HF signal obtained was noise-free with large bandwidth, having no signal cross-talks, electromagnetic interference, signal ringing, and signal reflections. Thus, offering good signal integrity and moderate circuit oscillations.

This designed project will immensely benefit optical communication systems requiring wide bandwidth, more immunity to EMI, crosstalk and transmission over long distances without degrading the signal. It can be used in Wireless Communication Systems such as mobile phones, wi-fi routers, etc., to enhance signal strength and range. It can be adopted for radar and sensing systems used in many industries, such as aerospace, defense, and healthcare

As new technologies emerge, high frequency amplifiers may find applications in areas, such as nanotechnology and photonics. These technologies often require precise and high-speed signal amplification, making high frequency amplifiers crucial for their development and advancement.

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