Particle Swarm Optimization for Comprehensive 24 GHz Amplifier Design

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Abstract In this paper, we report a computational autonomous design of a 24 GHz one-stage microwave amplifier, which is a key device for high-speed communication. A novel fitness function for particle swarm optimization (PSO) is introduced and a microwave amplifier is optimized by considering stability, center frequency, gain, and bandwidth. Moreover, we consider the parameters of PSO such as inertia coefficient, the number of particles, and topology to ensure immunity against a local optimum and accelerate the convergence. As a result, a 12 mW, 24 GHz amplifier, which has 10.8 dB gain and 3.8 GHz bandwidth, is designed autonomously in an hour.

Keywords: autonomous design, gain bandwidth product, microwave, stability, transmission line

1. Introduction

The unlicensed 24 GHz industrial scientific medical (ISM) band is used for detecting motion, such as by automatic doors, in Japan. There is a possibility that the 24 GHz band is suitable for high-speed communication because the band is broad in comparison with the other ISM bands of 2.4 and 5.8 GHz. Optical fibers, which are used for mobile communication backhaul, can be replaced with 24 GHz band communication owing to its high speed. As a result, fast recovery of the communication infrastructure from a disaster, communication services in mountainous areas and islands where the installation of optical fibers is difficult, and preparation for a temporary communication traffic explosion in a major event are possible.

To realize wireless communication, a corresponding amplifier is required. Since the impedance of parasitic capacitance is decreased at high frequencies, a feedback loop is formed by the parasitic capacitance and the mutual conductance of a field-effect transistor (FET) as shown in Fig.1(a). This feedback loop makes the circuit unstable and oscillate, which should be prevented in an amplifier because the oscillatory output is not related to the input even it has a huge gain at a resonance frequency \( f_r \) as shown in Fig.1(b). Although a method of breaking the feedback loop using a negative capacitance has been reported, the method increases the footprint of the circuit [1].

In the microwave region, a circuit block called a matching network (M.N.) is adopted for efficient power connection between the input (output) port and the FET gate (drain). If there is a reflection \( f_1 \) between the FET drain and the output matching network, the part of the power is fed back to the FET gate via the parasitic capacitance \( S_{12,FET} \). If there is a reflection \( f_2 \) between the FET gate and the input matching network, part of the feedback power is amplified by the FET \( S_{21,FET} \). This is an outline of the oscillation in a microwave circuit but the amounts of reflection \( f_1, f_2 \) can be controlled by the matching networks, whose careful design can avoid the oscillatory condition. Since the matching networks also determine the center frequency \( f_c \), power gain \( G_{peak} \), and bandwidth \( BW \) of the amplifier, they should be designed comprehensively while maintaining the stability of the circuit as shown in Fig.1(c).

Fig. 1 A feedback loop causes an unstable condition in a microwave amplifier because the reflected signal \( S_{12,FET} \) returns via the parasitic capacitance. The amounts of reflection \( f_1, f_2 \) can be controlled by matching networks (M.N.) and they should be designed considering the stability, center frequency \( f_c \), gain \( G_{peak} \) and bandwidth \( BW \).
Historically, computational autonomous RF circuit designs have been studied using linear programming (LP), nonlinear programming (NLP), genetic algorithms (GAs) and so on [2]. However, these algorithms have a defect, that the solution is sometimes trapped at a local optimum. It has been suggested that a relatively new optimization method called particle swarm optimization (PSO) can be applied for RF circuit design [3]. The optimization cost can be reduced using PSO because other methods such as simulated annealing (SA) require a vast number of iterative calculations for RF circuit design [4]. PSO is an algorithm inspired by the social behaviors of birds and fish, where the swarm has a direction but the individuals have a fluctuation, which helps to escape from a local optimum [5], [6]. Therefore, autonomous RF circuit designs using PSO have been reported recently [7]-[10]. However, the frequency range of the circuits is limited to 1.5-5.5 GHz and lumped elements are used in the circuits. On the other hand, a microwave circuit operating at 24 GHz uses distributed elements such as a transmission line because phase tuning is at the heart of the design. Since the response of the transmission line is a periodic function of the wavelength, the combination of these becomes a multi-hump function. Taking advantage of the fact that PSO can escape from a local optimum, several designs of a matching network have been reported [11]-[13]. In the microwave region, matching networks are designed with transmission lines but themselves do not need to consider the stability because they do not contain active elements. A microwave circuit design that contains active elements has been reported [14]. However, PSO is used only for reducing the port reflections around the active element ($F_1$ and $I_2$ of Fig.1(a)) and it is not used for optimizing the overall performance of the circuit.

The microwave amplifier design must consider multiple criteria such as stability, center frequency, gain, and bandwidth while avoiding a local optimum caused by a multi-hump function. In this paper, we propose an autonomous design of a microwave amplifier utilizing a novel method of dealing with multiple criteria and avoiding a local optimum owing to PSO. Additionally, we discuss the effects of the inertia coefficient $\omega$, the number of particles $n$, and the topology of the PSO through the 24 GHz amplifier design. This paper is composed as follows. Section 2 shows an amplifier circuit and the element models used in the circuit such as a FET and a transmission line. Section 3 introduces PSO and a novel fitness function that is suitable for the amplifier design. Section 4 gives the results of amplifier optimizations with a variety of PSO coefficients and topologies. Section 5 concludes this paper. Note that there are many PSO variants that enhance the optimization performance including the adaptive topologies. This paper is limited to the original PSO [5], [6] and typical topologies, and the conditions under which PSO is suitable for one-stage microwave amplifier design are investigated.

**2. Amplifier Circuit and Device Models**

Figure 2 shows a schematic of a 24 GHz one-stage amplifier. A FET is sandwiched between the input and output matching networks (M.N.). Each matching network is composed of four transmission lines (TLs), whose characteristics are determined by lengths $L_1$, $L_2$, $L_3$, $L_4$, $L_5$, $L_6$, $L_7$, and $L_8$. The input (output) matching network converts the input (output) port impedance into the gate (drain) impedance of the FET.

![Fig. 2 Schematic of a 24 GHz one-stage amplifier: A discrete FET is sandwiched between the input and output matching networks (M.N.). Each matching network is composed of four transmission lines (TLs), whose characteristics are determined by lengths $L_1$, $L_2$, $L_3$, $L_4$, $L_5$, $L_6$, $L_7$, and $L_8$. The input (output) matching network converts the input (output) port impedance into the gate (drain) impedance of the FET.](image)

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![Fig. 3 S-parameter of the discrete FET when the drain voltage and current are 2 V and 6 mA, respectively. The $S$-parameter was provided by California Eastern Laboratories (CEL) [15].](image)

![Fig. 4 Cross-sectional view of a transmission line (TL): The ground is a copper plane, and a signal copper line over a 1.6 mm glass-epoxy bulk (FR4) make up the microstrip line. The relative permittivity $\varepsilon_r$ and loss tangent $\delta$ are typical values for FR4.](image)
Figure 3 shows the scattering parameter (S-parameter) of the FET, which was provided by CEL Corporation [15]. Since its forward gain $S_{21}$ is less than 10 dB around the target frequency of 24 GHz and it has a high reflection $S_{11}$ at the input port, input and output matching networks are required to obtain a high gain with a sufficient bandwidth and less reflection. Figure 4 shows the cross-sectional view of a transmission line. This transmission line has the structure of a microstrip line and it was developed on a 1.6 mm-thick glass-epoxy bulk (FR4). Its relative permittivity $e_r$ and loss tangent $\tan \delta$ are typical values for FR4. Since the characteristic impedance $z_0$ of the microstrip line is dependent on the signal line width, the characteristic impedance $z_0$ as a function of the signal line width is estimated by EMPro, which is an EM simulator provided by Agilent Corporation, as shown in Fig.5 [16]. The characteristic impedance $z_0$ was found to be in accordance with the input/output port impedances of 50 Ω when the signal line width is 3 mm. The attenuation constant $\alpha$ and phase constant $\beta$ when the signal line width is 3 mm are shown in Fig.6. At 24 GHz, $\alpha$ and $\beta$ are 0.83 dB/cm and 571 deg/cm, respectively. Figure 7 shows the equivalent series resistance (ESR) and capacitance of proximity parallel transmission lines ($L_2$ and $L_9$ parts) estimated by the EM simulator with line gaps of 0.1, 0.2, and 0.3 mm. Although a smaller gap exhibits a higher capacitance, the 0.2 mm gap is chosen from the viewpoint of manufacturability.

The entire small-signal characteristic of Fig.2 can be calculated as a product of cascaded $T$-parameters $T_{\text{total}}$ as shown in Fig.8. All elements of the FET ($T_{\text{FET}}$), transmission lines ($T_{L1}$, $T_{L3}$, $T_{L4}$, $T_{L5}$, $T_{L6}$, $T_{L7}$, $T_{L8}$, $T_{L10}$), and parallel lines ($T_{L2}$, $T_{L9}$) are expressed with $T$-parameters and their product is converted into an $S$-parameter as a behavioral model of the amplifier [17]. This behavioral model is a function of the transmission line lengths.

$$T_{\text{total}} = T_{L1} \cdot T_{L2} \cdot T_{L3} \cdot T_{L4} \cdot T_{L5} \cdot T_{FET} \cdot T_{L6} \cdot T_{L7} \cdot T_{L8} \cdot T_{L9} \cdot T_{L10}$$

3. Particle Swarm Optimization and Fitness Function

To avoid trapping at a local optimum, PSO is applied for the amplifier design while considering stability, center frequency, gain, and bandwidth. As shown on the left-hand side of Fig.9, the PSO engine has multiple particles ($i \in \mathbb{N}$).
Each particle has position vector \( x_i \), velocity \( v_i \), personal best position \( p_i \), and global best position \( p_{gb} \), which are shared among the branch-connected particles (Fig.11). This PSO engine is the same as the original one [5], [6]. The position vector \( x_i \) contains the transmission line lengths \( \{L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}\} \) of the amplifier. When the position vector \( x_i \) is sent to the right-hand side of the optimization target, the \( S \)-parameter is calculated from the cascaded \( T \)-parameter elements (Fig.8). The figure of merit \( \text{FoM}_{PSO} \), which is a performance indicator and is explained in the next section, is calculated from the \( S \)-parameter and the value is fed to the left-hand side of the PSO engine as a fitness function \( g_i \). The personal best \( p_i \) is overwritten with the position vector \( x_i \) if the fitness value \( g_i \) is greater than before. The global best \( p_{gb} \) is updated when a better fitness function \( g_i \) is found among the branch-connected particles.

In the PSO engine, \( x_i \) and \( v_i \) are updated by the following equations.

\[
\begin{align*}
\dot{v}_i^{t+1} &= \omega \cdot v_i^t + c \cdot U_1 \cdot (p_i - x_i^t) + c \cdot U_2 \cdot (p_{gb} - x_i^t) \\
x_i^{t+1} &= \dot{x}_i^t + v_i^{t+1} \\
p_i &= x_i^t, \text{ if better } g_i \text{ is found} \\
p_{gb} &= \text{the best of } p_{j}, j \in \text{branch connected particles}
\end{align*}
\]

The constants \( \omega \) and \( c \) are called the inertia and memory/cooperation coefficients, respectively. \( U_1 \) and \( U_2 \) are random values uniformly distributed from 0 to 1. The first equation calculates the velocity of the particle \( v_i \), then the second equation updates the position vector \( x_i \). \( t \) denotes the number of iterations and \( x_i \) converges to the optimal location after sufficient iterations. A larger value of the inertia coefficient \( \omega \) gives large fluctuation of the positions and provides immunity from a local optimum at the cost of the convergence speed. The relationship between inertia \( \omega \) and memory/cooperation \( c \) is proposed to be as follows [6].

\[
\omega = \frac{1}{1 - c - \sqrt{c^2 - 2c}}
\]

Although the coefficients \( \omega \) and \( c \) are independent, the PSO does not give convergence when both \( \omega \) and \( c \) are large values. This equation balances the coefficients \( \omega \) and \( c \).

Although the PSO engine can avoid the local optimum, the calculation of the fitness function \( g_i \) is important for comprehensive amplifier design. Thus, the fitness function \( g_i \) should consider the stability, center frequency, gain, and bandwidth. The gain-bandwidth product \( \text{Gain BW} \) per unit power consumption \( P \) is often used as a figure of merit \( \text{FoM}_{AMP} \) of an amplifier as follows.

\[
\text{Gain BW} = 10 \cdot \text{Gain}_{\text{peak}[dB]} / 20
\]

\[
\text{FoM}_{\text{AMP}} = \frac{\text{Gain} \cdot \text{BW \ [Hz]}}{P \ [W]}
\]

In a small-signal amplifier, the power consumption \( P \) is constant and the gain-bandwidth product \( \text{Gain BW} \) can be...
calculated from its S-parameter. Although the gain and bandwidth are considered simultaneously using $FoM_{AMP}$, the stability and center frequency have not yet been considered. Therefore, we propose a new figure of merit $FoM_{PSO}$, which can also consider the stability and center frequency, using the following equations.

$$BW_{PSO} = 2 \cdot \min \{BW_{LSB}, BW_{USB}\}$$

(5)

$$FoM_{PSO} = \frac{Gain_{PSO} \cdot BW_{PSO} [Hz]}{P [W]}$$

(6)

Equation (5) divides the bandwidth $BW$ into the lower $BW_{LSB}$ and upper $BW_{USB}$ sides from the target frequency and the narrower one is doubled and assumed as the new bandwidth $BW_{PSO}$. The novel $FoM_{PSO}$ is obtained by substituting $BW_{PSO}$ in Eq. (5) for $BW$ in Eq. (4). As a result, in the case that the target frequency is located at the center of $BW$, $FoM_{AMP}$ and $FoM_{PSO}$ are equal because $BW_{AMP}$ and $BW_{PSO}$ are equal as shown in Fig.10(a). In the cases that the target frequency deviates from the center of $BW$ (Fig.10(b)) and it is outside of the $BW$ (Fig.10(c)), $FoM_{PSO}$ is smaller than that in the case of Fig.10(a). When the amplifier is unstable, a huge gain can be obtained at some resonance frequency (Fig.10(d)). However, $FoM_{PSO}$ is small because the bandwidth is so small and the gain-bandwidth product $Gain_{BW_{PSO}}$ cannot be large. Using this $FoM_{PSO}$ as the fitness function $g_x$, the PSO engine can optimize the circuit while considering the stability, center frequency, gain, and bandwidth.

Here, the term quality means the capability of optimization while avoiding a local optimum and reaching the same result regardless of the initial conditions. As the inertia coefficient $\omega$, 0.5, 0.7, and 0.9 are used. The memory/cooperation coefficient $c$ is determined from $\omega$ using Eq. (2). The numbers of particles are 25, 49, and 100. As the topologies, full (Fig.11(a)), mesh (Fig.11(b)), ring (Fig.11(c)), and wheel (Fig.11(d)) structures are used. The computational experiment is performed on a PC, which has an Intel Core i7-4790 3.6 GHz CPU, using MATLAB [18]. Figure 12 shows the convergence curve of $FoM_{PSO}$ as a function of iteration $t$ when the inertia coefficient $\omega$, the number of particles $n$, and the topology are 0.5, 100, and mesh, respectively. Each transmission line length $\{L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, or L_{10}\}$ is constrained from 0 to 10 cm. This graph shows the superposition of ten optimization results starting from random initial values of the position vector $x$. Although the initial values are different, all $FoM_{PSO}$ converge to similar values via different paths. In order to quantitatively evaluate the optimization quality and convergence speed, the quality index $\sigma$ and speed index $\delta$ are introduced. $\sigma$ is the difference between the best and worst values at $t = 1000$ iterations. A small value of $\sigma$ means high-quality optimization. $\delta$ is the difference between the average of the best and worst values at $t = 1000$ iterations and their average at $t = 500$ iterations. If the convergence is fast, $\delta$ becomes small because fast convergence achieves a nearly converged value at $t = 500$. A small value of $\delta$ also means fast convergence.

4. Experiments

In this section, we optimize the 24 GHz amplifier shown in Fig.2 using the PSO engine shown in Fig.9. Since the inertia coefficient $\omega$, memory/cooperation coefficient $c$, number of particles $n$, and topology affect the optimization quality and convergence speed, we discuss their effects when PSO is applied to a microwave amplifier design.
The quality $\sigma$ and speed $\delta$ indexes can be calculated from this table because it contains the best and worst values of $\text{FoM}_{\text{PSO}}$ at $t = 500$ and 1000. Figure 13 shows a scattering plot of $\sigma$ plotted against $\delta$ for each ID in Table 1. From the viewpoint of the speed $\delta$, the best inertia coefficient $\omega$ is 0.5. In this case, the particles move toward the tentative internal/global best position without much fluctuation and the search area of each particle is limited. This increases the probability of trapping at a local optimum, degrading the quality $\sigma$. However, this problem is mitigated by increasing the number of particles $n$ because the search area is covered by the increased number of particles. When $\omega$ is 0.7, the speed index $\delta$ is moderate. When $\omega$ is 0.9, $\delta$ is negative in some cases, which means the PSO engine finds a near-optimal point but misses the optimal point. There is a tendency that $\sigma$ and $\delta$ are improved with increasing $n$. The best topology is the mesh structure. This is because the global best position $p_{gb}$ propagates very fast (slow) in the full (wheel) structure preventing escape from a local optimum, whereas for the ring structure, a large $n$ degrades the optimization quality $\sigma$ because the propagation speed of $p_{gb}$ is an inverse function of $n$. Note that the ring structure may be superior to the mesh structure in terms of the quality $\sigma$ and speed $\delta$ if $n$ is carefully chosen.

Table 1 Best and worst cases of $\text{FoM}_{\text{PSO}}$ at $t = 500$ and 1000 iterations with a variety of topologies (Fig.11), inertia coefficients $\omega$, and numbers of particles $n$: Identifiers (ID) and computational times are also given.

![Table 1](https://example.com/table1.png)
As we discussed, the best optimization is performed with 500 iterations, which takes 59 min when the topology, inertia coefficient $\omega$, and number of particles $n$ are mesh, 0.5, and 100, respectively. In practical usage, the convergence curve in Fig. 12 is traced and the optimization is aborted when the change becomes less than a certain tolerance. The lengths of the transmission lines are rounded for manufacturability after this optimization. The rounded lengths and S-parameter as a function of frequency are shown in Fig.14. Upon rounding the lengths of the transmission lines, the performance of the amplifier is degraded by 5 % in terms of FoM PSO. As a result, the 24 GHz amplifier, which has 10.8 dB gain and 3.8 GHz bandwidth, is automatically designed with a power consumption of 12 mW. A high-performance microwave amplifier for high-speed communication can be realized efficiently and easily using this autonomous design method.

5. Conclusion

In this paper, we proposed the first ever method for optimizing a microwave amplifier while considering the comprehensive performances of stability, center frequency, gain, and bandwidth. We also explored the effects of the inertia coefficient, the number of particles, and the topology when PSO is applied to a microwave amplifier design. We found that the amplifier design can be autonomously performed in an hour. The designed 24 GHz amplifier has 10.8 dB gain and 3.8 GHz bandwidth with a power consumption of 12 mW. A high-performance microwave amplifier for high-speed communication can be realized efficiently and easily using this autonomous design method.
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