Terahertz surface plasmon-polaritons in one-dimensional graphene based Fibonacci photonic superlattices

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ARTICLE INFO
Article history:
Received 11 October 2017
Received in revised form 15 January 2018
Accepted 16 January 2018
Available online 30 January 2018

Keywords:
Graphene
Terahertz
Fibonacci
Quasi-periodic structure
Surface plasmon-polariton

ABSTRACT
The surface plasmon-polaritons in one-dimensional graphene-based Fibonacci photonic superlattices in the terahertz frequency range have been theoretically investigated. Our numerical study shows that surface plasmon-polaritons can be realized in both transverse electric and transverse magnetic polarizations. It is shown that these modes are manageable by varying the quasi-periodic generation orders which play a critical role in the occurrence of surface modes. In addition, the effect of thickness of cap layer and chemical potential of graphene sheets on surface plasmon-polaritons and their electric field distribution are studied. We have verified the excitation of surface plasmon-polaritons by using the attenuated total reflection method. This inspection confirms that all the predicted surface modes in the dispersion curves are actually excitable with this method.

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1. Introduction
There is a worldwide enthusiasm in plasmonics which is a significant part of photonics that deals with surface plasmon-polaritons (SPPs). SPPs are the electromagnetic waves that can propagate along the interface between metals and dielectrics and decay exponentially as a function of the distance from the surface. These waves are induced by coupling electromagnetic field to the electrons near the surface of a metal or semiconductor [1]. It has been observed that the properties of SPPs depend not only on the physical parameters of the constituent materials of layered structures but also on structural properties such as the ratio of the thickness of the alternating materials. One of the well-known examples of surface plasmon-polaritons is those that appear in the interface of metals and dielectrics [2–6]. But these structures have some disadvantages such as high losses, and absence of TE modes [1,7,8]. The mentioned disadvantages can be removed by presence of graphene in considered structure [7,9–14].

Graphene, a truly two-dimensional electronic system [15,16], has unusual and unique optical and electrical properties such as high carrier mobility [17], gate controllable Fermi level, and broadband electromagnetic response [18], which is desirable for tunable, high-speed, and broadband optoelectronic devices. Recently, graphene has emerged as promising terahertz (THz) materials [18] for efficient THz wave manipulation with intrinsic plasmons, which could bridge THz gap...
between microwave and far infrared regions [14]. THz frequency spectrum can be defined as the portion of the submillimeter wavelength electromagnetic spectrum between approximately 1 mm and 100 μm of wavelength (300 GHz–3 THz) [19]. THz technology has various interesting applications in different fields of information and communications.

Recently, there is an increasing interest in the research of SPPs in photonic crystals (PCs) which can control the propagation of electromagnetic (EM) waves in the same way as semiconductors do in controlling the movement of electrons [20,21]. On the other hand, there are other kinds of photonic band gap structures alternating between regular and random irregular structures which are defined by a simple mathematical rule. In the case of one-dimensional structures, they can be achieved by putting together several types of dielectric layers formed in accordance with the succession streams. Among them, Fibonacci, Tue- Morse, Rvdyn- Shapiro and Cantor sequences can be pointed out. These structures are remarkable because of their special characteristics [22].

SPPs in conventional quasi-periodic structures were studied in Refs. [23,24]. Considering the properties of surface modes in one-dimensional plasma PCs are the main subject of Ref. [25] and the surface modes in one-dimensional PCs containing graphene sheets were investigated in Ref. [26] which indicated the existence of TE surface modes in contrast with conventional structures. In this paper, we have theoretically studied the dispersion properties of SPPs at the interface of a semi-infinite bulk dielectric and a semi-infinite one-dimensional graphene based Fibonacci photonic superlattices (1DGFPS) in the THz frequency region. For this purpose, we are going to use the well-known transfer matrix method [27] for numerical analysis. We reveal the formation of SPPs for both the TE and TM polarizations in the presence of graphene and confirm this by attenuated total reflection (ATR) technique. This paper is organized as follows. In section 2, we introduce the theoretical model and basic relations for transfer matrix method and dispersion relations of SPPs. Results and discussions are given in section 3 and a conclusion is drawn in section 4.

2. Theoretical model and basic relations

In order to formulate the problem of realization of SPPs appearing at the interface of semi-infinite bulk dielectric and semi-infinite 1DGFPS, we consider a one-dimensional photonic crystal that each cell of its own is composed of a Fibonacci quasi-periodic structure. This structure consists of two homogeneous materials A and B with dielectric constants $\varepsilon_A$ and $\varepsilon_B$ and thicknesses $d_A$ and $d_B$ and graphene monolayers with optical conductivity $\sigma$ as indicated in Fig. 1. Here, layers lie in the x–y plane, and z axis is perpendicular to the interface of layers and a cap layer is placed between dielectric and 1DGFPS. The material of cap layer is the same as that of A layers with thickness $d_c$ which is started from $z = -d_c$ and ended at $z = 0$ and the rest of the structure which is a periodic structure with the Fibonacci quasi-periodic unit cell, started at $z = 0$.

Quasi-periodic structures are composed of the superposition of two (or more) building blocks that are arranged in a desired manner. Fibonacci multilayer photonic structure can be grown by juxtaposing two building blocks A and B, in such a way that the N’th-order of the superlattice $S_N$ is given iteratively by the rule $S_N = S_{N-1}S_{N-2}$, for $N \geq 2$, with $S_0 = B$ and $S_1 = A$. According to this inflation rule, the sequential Fibonacci chains are $S_2 = AB, S_3 = ABA, S_4 = ABAAB, S_5 = ABAABABA$, and so on. The number of the building blocks increases according to the Fibonacci number, $F_N = F_{N-1} + F_{N-2}$ (with $F_0 = F_1 = 1$), and the ratio between the number of building blocks A and the number of building blocks B in the sequence equals to the golden mean number $\tau = \frac{1 + \sqrt{5}}{2}$. This multilayered photonic structure could also be grown by the inflation rule: $A \rightarrow AB, B \rightarrow A$ [28].

We contemplate a polarized monochromatic EM wave which is incident on the 1DGFPS at $z = -d_c$. For the case of TE polarized monochromatic EM waves, electric and magnetic fields are written as follows

$$E = E_y(z)\hat{e}_y e^{i(k_0 x - \omega t)},$$
$$H = [H_x(z)\hat{e}_x + H_z(z)\hat{e}_z]e^{i(k_0 x - \omega t)},$$

in which, $\omega$ is the angular frequency, $k = \frac{\omega}{c}$ is the vacuum wave number, and $\beta k = k_0$ is the x–component of the wave vector. The solution of Maxwells equation for $E(z)$ and $H(z)$ in the l-th layer are written as

![Fig. 1. Schematic diagram of 1DGFPS. This structure consists of a semi-infinite bulk dielectric and a semi-infinite photonic crystal where each unit cell of its own is composed of the fourth generation of Fibonacci sequence and graphene monolayers are placed between the adjacent layers.](image-url)
\[
E_{p}(z) = \begin{cases} 
q_{e}e^{i{k_{v}(z-z_{i})}} + b_{e}e^{-i{k_{v}(z-z_{j})}} & \text{if } z < -d_{c} \\
q_{e}e^{i{k_{v}(z-z_{j})}} + b_{e}e^{-i{k_{v}(z-z_{i})}} & \text{if } z \geq -d_{c},
\end{cases}
\]

(3)

\[
H_{k}(z) = \frac{1}{\hbar} \mu_{0} \times \begin{cases} 
\frac{1}{\mu_{v}}q_{e}e^{i{k_{v}(z-z_{i})}} & \text{if } z < -d_{c} \\
\frac{1}{\mu_{v}}(i\alpha_{e}q_{e}e^{i{k_{v}(z-z_{j})}} - ib_{e}e^{-i{k_{v}(z-z_{i})}}) & \text{if } z \geq -d_{c},
\end{cases}
\]

(4)

here \(\mu_{0}\) is the magnetic permeability of vacuum and \(\mu_{v}\) and \(\mu_{l}\) are respectively the relative magnetic permeability of medium \(v\) and \(l\)-th layer. \(k_{vz}\) and \(k_{lz}\) are respectively the \(z\)-component of the wave vectors in medium \(v\) and \(l\)-th layer in the \(z\)-direction which equal to

\[
k_{vz} = \frac{\omega}{c} \sqrt{\beta^{2} - n_{v}^{2}},
\]

(5)

\[
k_{lz} = \frac{\omega}{c} \sqrt{n_{l}^{2} - \beta^{2}},
\]

(6)
in which \(n_{v}\) and \(n_{l}\) are the refractive index of medium \(v\) and \(l\)-th layer, respectively. By applying boundary the conditions at the beginning and end of each unit cell on the field components and using the transfer matrix method \([27]\), we have

\[
\left( \begin{array}{c}
\alpha_{p+1} \\
\beta_{p+1}
\end{array} \right) = M \left( \begin{array}{c}
\alpha_{p} \\
\beta_{p}
\end{array} \right) = \left( \begin{array}{cc}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{array} \right) \left( \begin{array}{c}
\alpha_{p} \\
\beta_{p}
\end{array} \right),
\]

(7)

where \(p\) is the number of unit cell, and \(M_{ij}\) with \(i, j = 1, 2\) are the elements of transfer matrix of a single unit cell. For example, we write a unit cell transfer matrix for the Fibonacci 3rd generation

\[
M = G_{AA} P_{A} G_{BA} P_{B} G_{AB} P_{A},
\]

(8)

\(P_{j}\) with \(j = A, B\) is propagation matrix

\[
P_{j} = \left( \begin{array}{cc}
e^{ik_{jd_{j}}} & 0 \\
0 & e^{-ik_{jd_{j}}}
\end{array} \right),
\]

(9)

and \(G_{jj}\) with \(j = A, B\) is the transfer matrix which relates the electric field coefficients at two side of adjacent layers \(j\) and \(j\) written as

\[
G_{jj} = \frac{1}{2} \left( \begin{array}{cc}
1 + \frac{k_{jz}}{k_{fjz}} - \frac{\alpha_{0}\omega}{k_{fjz}} & 1 - \frac{k_{jz}}{k_{fjz}} + \frac{\alpha_{0}\omega}{k_{fjz}} \\
1 - \frac{k_{jz}}{k_{fjz}} + \frac{\alpha_{0}\omega}{k_{fjz}} & 1 + \frac{k_{jz}}{k_{fjz}} - \frac{\alpha_{0}\omega}{k_{fjz}}
\end{array} \right).
\]

(10)

The frequency-dependent optical conductivity of graphene monolayer is obtained from Kubo formula \([29,30]\) including the intraband and interband transition contributions as:

\[
\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}},
\]

(11)

where for high frequencies \((\omega \gg k_{B}T^{-1})\) at temperature \(T\) in the random-phase approximation, \(\sigma_{\text{intra}}\) and \(\sigma_{\text{inter}}\) are in the form of \([31,32]\),

\[
\sigma_{\text{intra}} = \frac{\gamma^{2}}{4h} \frac{q_{e}^{2}}{2\pi} \ln \left[ 2 \cosh \left( \frac{\mu_{c}}{k_{B}T} \right) \right],
\]

(12)

\[
\sigma_{\text{inter}} = \frac{\gamma^{2}}{4h} \frac{1}{\pi} \arctan \left( \frac{h_{\omega} - 2\mu_{c}}{2k_{B}T} \right) - \frac{i}{2\pi} \ln \left( \frac{(h_{\omega} + 2\mu_{c})^{2} + (2k_{B}T)^{2}}{(h_{\omega} - 2\mu_{c})^{2} + (2k_{B}T)^{2}} \right),
\]

(13)

here \(e\) is the charge of an electron, \(k_{B}\) is the Boltzmann constant, \(\mu_{c}\) is the chemical potential which is tunable via gate voltage, \(T\) is the temperature at Kelvin.

Dispersion relation of TE surface waves can be obtained by applying the boundary conditions at \(z = -d_{c}\) and choosing the damped wave solutions for distances far from the interface
\begin{equation}
\frac{M_{\delta z}}{M_{\delta z}} = \frac{\sigma_{\delta z} - \sigma_{\delta z}}{\mu_{\delta z}} = \frac{\lambda - M_{11} - M_{12} e^{-2 i k_0 d_c}}{\lambda - M_{11} + M_{12} e^{-2 i k_0 d_c}},
\end{equation}

where $\lambda = \text{real}(M_{11}) \pm \sqrt{\text{real}(M_{11}) - 1}$.

For TM waves, electric and magnetic fields are written as follows

\begin{equation}
\mathbf{H} = H_y(z) \mathbf{\hat{e}}_y e^{i(k_0 z - \omega t)},
\end{equation}

\begin{equation}
\mathbf{E} = [E_x(z) \mathbf{\hat{e}}_x + E_z(z) \mathbf{\hat{e}}_z] e^{i(k_0 z - \omega t)},
\end{equation}

where, the tangential components of electromagnetic fields are assumed as

\begin{equation}
H_y(z) = \begin{cases} 
\frac{b_n e^{i k_0 z}}{i \epsilon_n} + \frac{b_f e^{-i k_0 z}}{i \epsilon_f} & \text{if } z < -d_c, \\
\frac{1}{i \epsilon_f} (i q_0 e^{i k_0 z} - i b_f e^{-i k_0 z}) & \text{if } z > -d_c,
\end{cases}
\end{equation}

\begin{equation}
E_x(z) = \frac{1}{i \omega \epsilon_0} \times \begin{cases} 
\frac{1}{i \epsilon_f} & \text{if } z < -d_c, \\
\frac{1}{i \epsilon_f} (i q_0 e^{i k_0 z} - i b_f e^{-i k_0 z}) & \text{if } z > -d_c,
\end{cases}
\end{equation}

where $\epsilon_0$ is the electric permittivity of vacuum and $\epsilon_n$ and $\epsilon_f$ is respectively the relative electric permittivity of medium $n$ and $f$th layer. The transfer matrix which relates the magnetic field coefficients at two side of adjacent layers $j$ and $j+1$ is written as

\begin{equation}
G_{j+1} = \frac{1}{2} \begin{pmatrix} 
1 + \frac{e_j k_{j+1}^z}{\epsilon_j k_{j+1}^z} & \frac{-\sigma k_{j+1}^z}{\epsilon_0 \epsilon_f} \epsilon_j k_{j+1}^z \\
-\frac{\sigma k_{j+1}^z}{\epsilon_0 \epsilon_f} \epsilon_j k_{j+1}^z & 1 + \frac{e_j k_{j+1}^z}{\epsilon_j k_{j+1}^z}
\end{pmatrix}.
\end{equation}

In a similar way, one can find the following dispersion relation for TM waves

\begin{equation}
-i \frac{\epsilon_s}{\epsilon_A} k_{\delta z} + \frac{\sigma k_{\delta z}}{\omega \epsilon_0 \epsilon_A} = \frac{\lambda - M_{11} + M_{12} e^{-2 i k_0 d_c}}{\lambda - M_{11} - M_{12} e^{-2 i k_0 d_c}}.
\end{equation}

In order to find the solutions of dispersion relation, we have to solve Eqs. (14) and (20) numerically since they have no exact analytical solutions.

Based on the transfer matrix method, one can easily calculate the optical spectra such as reflection and transmission for layered structure as

\begin{equation}
r = \frac{M_{21}}{M_{11}}, \quad t = \frac{1}{M_{11}}.
\end{equation}

Therefore, the reflectance and transmittance can be calculated for both the TE and TM polarizations via $r$ and $t$ [27].

3. Results and discussion

In this paper, we investigate the existence of the TE and TM SPPs at the interface between a uniform medium, $\nu$, and a semi-infinite 1DGFPS with a cap layer. We suppose that the cap layer of the periodic structure has the width $d_c$ which is different from the width of other layers of the structure. For the numerical calculation, we choose $d_A = d_B = 28 \mu m$, $\mu_A = 3.8$, $\mu_A = 1$ (which are corresponding to silica glass), $\epsilon_B = 2.04$, $\mu_B = 1$ (Teflon), $T = 300 K$ and $\epsilon_c = 0.2 eV$ [33,34]. Since the electromagnetic waves must decrease exponentially on both sides of the interface, we only have to choose those values of $\beta$ which satisfy the following relation

\begin{equation}
\beta^2 > \max\{n_\nu, n_A, n_B\}.
\end{equation}

In Fig. 2, we indicate the band structure and the dispersion curves of SPPs for the 2nd generation of Fibonacci quasi-periodic structure, which is equivalent to the periodic structure, in both the TE and TM modes for different values of cap layer thickness in the $\beta$-frequency plane. In this figure, the light yellow and the green regions display allowed bands for the TE and TM modes respectively, whereas the white regions refer to forbidden band gaps. It is found that in this structure, including graphene sheets, the SPPs can occur (shown by lines in Fig. 2) in both polarizations of TE and TM modes unlike the
structures without graphene sheets which support only the TM modes. Comparing the dispersion properties of the TE and TM modes reveals that the sensitivity of TE modes to the changing of the cap layer thickness is greater than that of the TM modes. In the case of the TM mode, the width of the second band gap vanishes for a definite \( \beta \), corresponding to Brewster's angle, which we show by \( \beta_B \). It is clear that for a given \( d_c \), the structure can support SPPs with \( \beta < \beta_B \) or \( \beta > \beta_B \).

Now, we intend to find how the quasi-periodic generation orders affect the dispersion properties of the SPPs. Fig. 3 shows the band structures and dispersion curves of SPPs for the 2nd to 5th generation of Fibonacci quasi-periodic structure for the TE polarization. One can see that the Fibonacci quasi-periodic generation order plays an important role in the occurrence of SPPs. The higher Fibonacci quasi-periodic generation order, the more numbers of photonic band gaps; hence the more

Fig. 2. Band structure and dispersion curves of SPPs for the 2nd generation of Fibonacci quasi-periodic structure (which is equivalent to periodic one) in both the TE and TM modes for different values of cap layer thickness. In this figure \( d_A = d_B = 28 \mu m, \varepsilon_A = 3.8, \mu_A = 1, \varepsilon_B = 2.04, \mu_B = 1, T = 300 K \) and \( \mu_c = 0.2 \mathrm{eV} \).

Fig. 3. Band structure and dispersion curves of SPPs for (a) second, (b) third, (c) fourth and (d) fifth Fibonacci quasi-periodic generation for TE polarization. Here \( d_c = 0.3 d_A \) and the other parameters are the same as Fig. 2.
numbers of surface modes in some definite frequency ranges. Therefore, increasing of the quasi-periodic generation order is a critical parameter for the increment of the number of surface modes in a given frequency range for both the TE and TM modes (see Figs. 3 and 4). Fig. 4 depicts the band structures and dispersion curves of SPPs for the 2nd to 5th generation of Fibonacci quasi-periodic structure for TM polarization. From this figure we observe that the range, in which SPPs can occur in the TM mode, is limited in comparison to the TE mode. The figure also shows that the number of band gaps and dispersion curves increases as the generation order of Fibonacci quasi-periodic structure goes higher.

For a more detailed investigation, the excitation of the SPPs has been verified by ATR method. This technique has previously been invoked for the investigation of various types of surface polaritons, e.g., plasmon polaritons in metals, phonon polaritons in ionic crystals, exciton polaritons in semiconductors, and magnon polaritons in magnetic materials [35–37]. We consider the ATR geometry shown in Fig. 5, in which the left side medium is a semi-cylinder prism with refractive index

![Fig. 4. Band structure and dispersion curves of SPPs for (a) second, (b) third, (c) fourth and (d) fifth Fibonacci quasi-periodic generation for TM polarization. Here $d_c = 0.3 d_A$ and the other parameters are the same as Fig. 2.](image)

![Fig. 5. Principle of the excitation of SPPs using ATR geometry in 1DGFPS.](image)
**Fig. 6.** Reflectance spectra obtained from ATR technique for different Fibonacci quasi-periodic generations (a) $S_2$ with $\beta = 1.2$, (b) $S_3$ with $\beta = 1.3$, (c) $S_4$ with $\beta = 1.2$ and (d) $S_5$ with $\beta = 1.4$. Here $d_c = 0.3 \, d_A$ and other parameters are the same as **Fig. 2**.

**Fig. 7.** Dependence of band structure and dispersion curves of SPPs on the chemical potential of graphene sheets, $\mu_c$, for the 3rd Fibonacci quasi-periodic generation in both the TE and TM polarizations. Here $\beta = 1.2$ and solid and dashed lines correspond to $d_c = 0.2 \, d_A$ and $d_c = 0.3 \, d_A$, respectively. The other parameters are the same as **Fig. 2**. Points 1 to 9 indicate those modes that their electric field profiles will be plotted in **Fig. 8**.
$n_p = 2$, the middle medium is air with thickness $d_v = d_A$, and the right side medium is a 1DGFPS illustrated in Fig. 1. For an incident angle larger than the angle of the total internal reflection, the electromagnetic field incident from an optically dense medium (a prism with refractive index $n_p > n_v$) will penetrate the gap layer as an evanescent wave, which can interact with the SPP mode in order to excite it. When the excitation of SPPs occurs, a dip will appear in the intensity of the reflected beam which is obvious in the reflectance spectrum [1]. In other words, the dip determines the frequency for which the resonance can occur for the excitation of an SPP for a given $\beta$. In Fig. 6 we have calculated the reflectance of the ATR geometry for the 2nd to 5th Fibonacci quasi-periodic generation for different angles of incidence (or different $\beta = n_p \sin(\theta)$) for TE polarization. It is clear that this figure is completely in agreement with Fig. 3. For example, in Fig. 6(b) in the 3rd generation of Fibonacci quasi-periodic structure ($S_3$) at $\beta = 1.3$, there are three resonance dips corresponding to the three possibilities of the excitation of Fig. 8.

![Electric field profiles of SPPs in 3rd Fibonacci quasi-periodic generation for $\beta = 1.2$ and $d_v = 2d_A$ in TE polarization: (a) for points “1–3” in Fig. 7, (b) for points “4–6” in Fig. 7 and (c) for points “7–9” in Fig. 7. Insets in part (a), (b) and (c) show the intensity profiles for points “3, 6 and 9” in Fig. 7, respectively. The other parameters are the same as Fig. 7.](image-url)
SPPs at the same β in Fig. 3(b). These dips confirm three SPPs with frequencies 0.84, 1.84, and 2.96 THz. Therefore, in accordance with ATR method, all of the predicted surface modes in the dispersion curves in Fig. 3 are excitable and realizable.

Fig. 7 illustrates the effect of chemical potential of graphene sheets on band structure and dispersion curves of SPPs for the 3rd generation of Fibonacci quasi-periodic structure for both the TE and TM polarizations in β = 1.2 and two different values of δc. As we can see from this figure, by increasing μc in given β, the location of band gaps and the SPP modes are shifted to higher frequencies. This feature enables us to adjust the SPPs via tuning of the μc.

Finally, for a better understanding of the configuration of SPPs, we represent the electric field profile of these modes for the 3rd Fibonacci quasi-periodic generation in TE polarization at the interface of semi-infinite dielectric medium and a 1DGFPS in the THz frequency range. Our numerical calculations showed that these modes have the tuning capability by changing the quasi-periodic generation orders. The higher quasi-periodic generation order, the more numbers of SPP modes. The excitation of SPPs was verified by ATR method, in which the reflectance diagram is represented by using the well-known prism coupling method. The results were completely in agreement with those of dispersion curves of SPPs. On the other hand, the effect of thickness of cap layer and the chemical potential of graphene sheets on the band structure and dispersion curves of SPPs was revealed. It was found that SPP modes are adjustable by tuning the thickness of cap layer and the chemical potential of graphene sheets, e.g., by increasing μc, for given β SPP modes are shifted to higher frequencies. Finally, the electric field profile of SPPs was depicted in order to clarify the configuration of SPPs.

4. Conclusion

To summarize, we studied the existence of SPPs in both the TE and TM polarizations at the interface of semi-infinite dielectric medium and a 1DGFPS in the THz frequency range. Our numerical calculations showed that these modes have the tuning capability by changing the quasi-periodic generation orders. The higher quasi-periodic generation order, the more numbers of SPP modes. The excitation of SPPs was verified by ATR method, in which the reflectance diagram is represented by using the well-known prism coupling method. The results were completely in agreement with those of dispersion curves of SPPs. On the other hand, the effect of thickness of cap layer and the chemical potential of graphene sheets on the band structure and dispersion curves of SPPs was revealed. It was found that SPP modes are adjustable by tuning the thickness of cap layer and the chemical potential of graphene sheets, e.g., by increasing μc, for given β SPP modes are shifted to higher frequencies. Finally, the electric field profile of SPPs was depicted in order to clarify the configuration of SPPs.

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