Power Breakdown Threshold of a Plasmonic Waveguide Filter

P. A. Calva · I. Medina

Abstract The services provided by satellite communications are continuously increasing, and this demands a higher bandwidth and power consumption. The current devices involved with this problem are waveguides and filters. Recent research shows the technological limit of these macro-devices, so that it is necessary to work in new designs using higher frequency than microwaves, because the power consumption would be reduced and the data rate would increase from 195 Gbps to 5,600 Tbps. The use of optical communications in satellites would help to satisfy the demand of new services. In this article, the use of plasmonic waveguide filters is proposed to demultiplex signals in real time instead of the use of digital grating processors (DGP). These filters operate with surface plasmon polaritons in a metal-insulator-metal structure. Their power breakdown threshold is obtained and analyzed in a variable pressure range and operating at different wavelengths.

Keywords Plasmonic waveguide filters · Power breakdown · Optical communications

Introduction

The demand of the services offered by artificial satellites is continuously increasing, and this implies higher bandwidths and higher power consumption; this in turn can generate corona and multipactor effects in filters and waveguides.

The current waveguide filters have reached their technological limits [1]. The low bit rate encoding allows sending of up to 16 bits of information per Hertz [2], considering the current Ku-type filters operating at a frequency of 12.2 GHz. The amount of data sent is only of 195.2 Gbps, and by using optical communications in satellites, with an operating frequency of 350 THz, the bit rate will be able to deliver up to 5,600 Tbps. Recent researches have proposed the use of wavelength divisor multiplexor (WDM) polymer substrate mode photonic interconnects for satellite communications [3]; incoming signals can be directly coupled into one system chip without any intermediate optical-electrical and electrical-optical conversions, in cooperation with reconfigurable digital grating processors (DGP), so the system can achieve power and wavelength management [3]. The main advantages of the substrate mode photonic interconnectors are as follows: integrated robust planar platform, insensitivity to mechanical and environmental perturbations, low propagation losses, compatibility with surface mount technology, and low cost. However, these DGPs are active components that require energy to operate and have a delay time because of the electronic processing. In this article, it is proposed to substitute the DGPs by passive devices to demultiplex the signals by means of plasmonic waveguide filters connected in the grating section of the substrate.

The DGPs are multilayered planar devices and have several digital electrodes, and by applying voltage to different electrodes, it can be configured to have different slanted angles, to phase match optical signals with different input and output angles, and be configured to have different responding wavelengths of signals. Plasmonic waveguide filters can be also planar devices and could be possible to connect directly on the grating section of the substrate, so they could transmit information at different frequencies at the same time; also, surface plasmons travel on flat surfaces at velocities close to the speed of light and transport optical and electrical signals at the same

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time, making these optical devices faster than the proposed DGPs [4, 5]. However, this option has the disadvantage that electrical breakdown can occur due to the phenomenon of ionization. In addition, in these filters, it is necessary to consider that the light emitting in the optic range penetrate metals of up to 30 nm deep. This facilitates the generation of surface plasmons [4]. Under specific conditions, incident light couples with the surface plasmons to create self-sustaining, propagating EM waves known as surface plasmon polaritons (SPPs) [5].

Figure 2 shows an example of a plasmonic waveguide filter; all the information regarding the design of the filter, transmission spectra, and optimal lengths are extracted from [6].

This filter based on metal-insulator-metal (MIM) structure has multiple outputs; each one can supply a specific channel in a big range of wavelengths. These types of filters are formed by an arrangement of nanometric waveguides, all with the same gap distance. Inside them are multiple resonance modes, and the first and second modes can go out through the waveguides localized in the center and three quarters of the structure, respectively. The SPPs propagate along the Z-axis of the main plasmonic waveguide, as shown in Fig. 1; the resonance occurs when the SPPs are captured inside the middle cavity. The resultant filtered wavelengths are dependent of the size of this middle cavity, and by changing its length, these filters can deliver a very wide range of wavelengths from 500 to 10,000 nm. The optimal lengths of the middle waveguide to make this filter transmit different wavelengths are $L=280$, 320, 350, 360, and 390 nm, and the transmitted wavelengths are $\lambda=575$, 850, 1,060, 1,310, and 1,550 nm, respectively.

It should be noted that the coupling distances to generate the resonance in the middle cavity and the output ports are only achieved when the distances d_1 and d_2 are smaller than the field skin depth, less than 30 nm for silver [7]; so, in this case, d_1 and d_2 are proposed as 10 and 15 nm, respectively. The gap distance of all the waveguides is $W=50$ nm.

These filters have very good transmission spectra and can easily operate in wavelengths from 575 to 1,500 nm, being optimal for using them in the proposed optical communication satellite. However, it is necessary to consider the breakdown
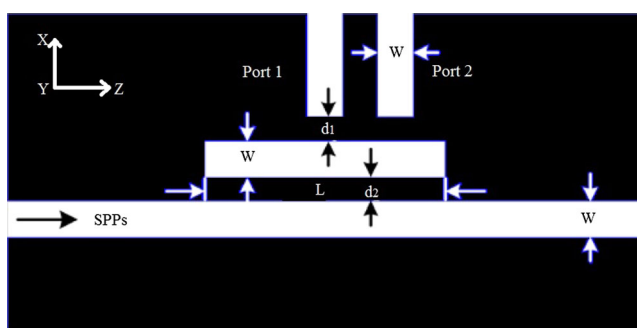
power threshold of these types of filters due to photoionization in order to know the overall power consumption.

Surface Plasmon Polariton Breakdown Analysis in MIM Structure

To analyze the electromagnetic waves in an excited surface, it is needed to consider the distribution of the electrons that are not in equilibrium and generated as a result of light absorption. The linear and multiphotonic absorption results in the generation of electrons that are not in equilibrium; then, during the diffusion, the electrons excited by photons and the unbalanced electrons generate an energy exchange through electron-electron collisions. The equation that describes the evolution of the free electron density excited by the photon energy in time is as follows [8]:

$$\frac{\partial n}{\partial t} = D\nabla^2 n + \frac{(1-R)\alpha_1 I}{\hbar\omega} + \frac{(1-R)^2\alpha_2 I^2}{2\hbar\omega} - \frac{n}{\langle\tau_{ee}\rangle} \tag{1}$$

where D is the electronic diffusion coefficient, $\langle\tau_{ee}\rangle$ is the time between the electron-electron collisions, I is the irradiance of the light in watts per square meter, R is the reflection coefficient, α_1 is the linear photonic absorption coefficient, and α_2 is the two-photon absorption coefficient.

The breakdown condition, for the case of continuous wave operation, is the following [9]:

$$\frac{\partial n}{\partial t} = 0 \tag{2}$$

Also, considering the next equation,

$$-\frac{\nabla^2 n}{n} = \frac{1}{\Lambda_{eff}} \tag{3}$$

where Λ_{eff} is the effective diffusion length. This way, the electronic and photonic intervention in the breakdown process due to the surface plasmon polaritons is obtained:

$$\frac{1}{\Lambda_{eff}} = \left(\frac{(1-R)\alpha_1 I}{\hbar\omega} + \frac{(1-R)^2\alpha_2 I}{2\hbar\omega} - \frac{n}{\langle\tau_{ee}\rangle}\right)/nD \tag{4}$$

According to [10], there is no two-photon absorption for the cases where the plasmon has an angular momentum of $l>1$. $l=1$ corresponds to the bipolar resonance of the plasmon, which is the one that occurs in these types of filters [6]. Then, Eq. (4) is reduced to the following:

$$\frac{1}{\Lambda_{eff}} = \left(\frac{(1-R)\alpha_1 I}{\hbar\omega} - \frac{n}{\langle\tau_{ee}\rangle}\right)/nD \tag{5}$$

Fig. 1 Two-channel plasmonic waveguide filter structure

Substituting $\frac{1}{\langle \tau_{ee} \rangle} = \nu_c \equiv$ collision frequency,

$$\frac{1}{\Lambda_{\text{eff}}} = \frac{(1-R)\alpha_1 I}{\hbar \omega n D} - \frac{\nu_c}{D} \qquad (6)$$

The lineal photonic absorption coefficient is obtained using the following [11]:

$$\alpha_1 = 4\pi \overline{k}/\lambda \left[\text{cm}^{-1}\right]. \qquad (7)$$

where $\overline{k}$ is the extinction coefficient, and λ is the wavelength; Table 1 shows the experimentally obtained values in [11] for the extinction coefficients at a specific wavelength and the corresponding absorption coefficients.

The electron density in the electrical breakdown threshold is as follows [12]:

$$n = 1.1 \cdot 10^{15} \left[\text{cm}^{-3}\right] \qquad (8)$$

The reflection coefficient of silver is the following [12]:

$$R = 0.95 \qquad (9)$$

The $\hbar\omega$ term is the energy of a photon, where ω is the angular frequency and $\hbar$ is the Planck constant divided by 2π:

$$\hbar\omega = \frac{h2\pi f}{2\pi} = hf = 6.62 \cdot 10^{-34} f \, [J] \qquad (10)$$

The diffusion coefficient in air, independent of the electric field, is as follows [9]:

$$D = \frac{10^6}{p} \left[\text{cm}^2 \text{s}^{-1}\right] \qquad (11)$$

The collision frequency is as follows [13]:

$$\nu_c = 5 \cdot 10^9 p \left[\frac{\alpha}{\alpha + 8}\right]^{1/2} \qquad (12)$$

The effective diffusion length is defined as follows [14]:

$$\frac{1}{\Lambda_{\text{eff}}^2} = a^{-2} \sqrt{\pi^4(1 + 0.3677\beta) + \frac{\pi^2 \beta q}{2} + \left(\frac{\pi}{b}\right)^2} \qquad (13)$$
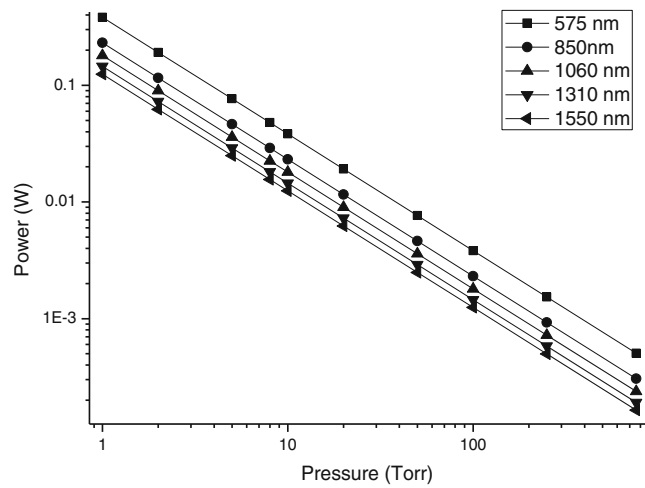

Fig. 2 Power breakdown threshold of a two-channel plasmonic waveguide filter at different wavelengths

where

$$q = \left(\frac{a}{L_a}\right)^2 + \left(\frac{\pi a}{b}\right)^2 \qquad (14)$$

β is a parameter that depends on the employed gas, for air is $\beta = 5.33$, and the value of L_a is calculated using the following [14]:

$$L_a = \sqrt{\frac{D}{\nu_a}} \qquad (15)$$

where the attachment frequency is as follows [9]:

$$\nu_a = \nu_{a2} + \nu_{a3} \qquad (16)$$

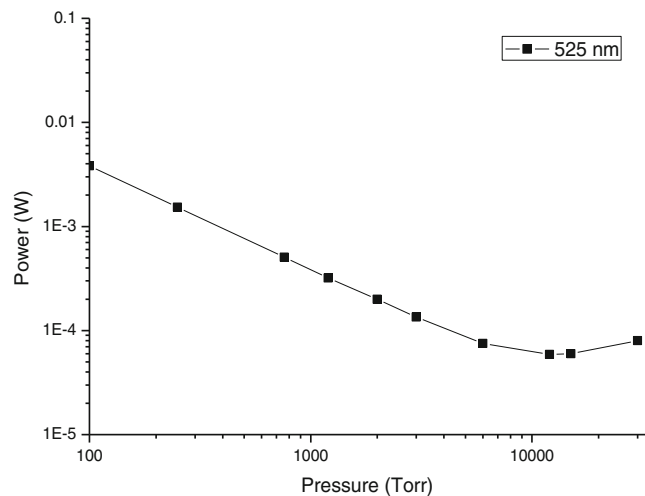| Table 1 Experimental values for the extinction and linear photonic absorption coefficients	Wavelength (nm)	Extinction coefficient $\overline{k}$	Absorption coefficient (cm^{-1})
	575	3.45	7.54E+05
	850	5.70	8.43E+05
	1,060	7.33	8.69E+05
	1,310	9.10	8.73E+05
	1,550	10.60	8.59E+05

Fig. 3 Paschen minimum of plasmonic waveguide filter operating at a wavelength of 525 nm

The two-body attachment frequency is defined as follows [13]:

$$v_{a2} = 7.6 \times 10^{-4} p \varphi^2 (\varphi + 218)^2 \left[s^{-1} \right] \qquad (17)$$

And the three-body attachment frequency is as follows [9]:

$$v_{a3} = 10^2 p^2 \left[s^{-1} \right] \qquad (18)$$

with

$$\varphi = \frac{E_{\text{rms}}}{p \left(1 + \frac{\omega^2}{v_c^2} \right)^{\frac{1}{2}}} \equiv \frac{E_{\text{eff}}}{p} \qquad (19)$$

Figure 2 shows the results of the power breakdown threshold in a wide range of atmospheric pressure at different wavelengths.

It can be seen that, as atmospheric pressure decreases, the power breakdown threshold is higher, locating the lower values at sea-level pressure. This is important because, when handling this equipment in earth stations, the designers must be aware of the minimum breakdown level and operate below it, raising it as the satellite goes into orbit. This is a different behavior from the waveguide filters currently used in satellites, where the power breakdown decreases as the pressure lessens.

These extremely low power values are not a problem in the data transmission, according to [15]; the earth stations are capable of receiving very low optical powers of $P = 4 \cdot 10^{-14}$ W.

Figure 3 shows that it would be necessary to reach extreme pressures (about 10,000 torr) for having the Paschen minimum.

Conclusions

When using polymer substrate mode photonic interconnects for satellite communications, it is possible to substitute the DGPs located on the grating region of the substrate by plasmonic waveguide filters. The main advantage is being passive devices; however, it is necessary to consider the presence of surface polaritons that can contribute to electrical breakdown if the threshold power is exceeded.

The power threshold of plasmonic waveguide filters can be obtained with the equation that describes the evolution of the free electron density excited by the photon energy in time (1). For wavelengths from 575 to 1,500 nm, the power threshold is

in the range of 0.1 to 0.4 W at 1 torr in atmospheric air. These power thresholds are enough for electronic processing. Additionally, it is observed that the Paschen minimum is not present at 760 torr or smaller values.

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